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BITUMINOUS SOIL STABILIZATION

A THESIS

Presented to

the Faculty of the Graduate Division

by

Walton Davison Gale

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Civil Engineering

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BITUMINOUS SOIL STABILIZATION

Approved______________________
Radnor J. Paquette

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Donald O. Covault

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George F. Sowers

Date approved by Chairman May 26, 1962

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ACKNOWLEDGEMENTS

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Grateful appreciation is extended to my wife, Anne, whose unwavering loyalty and constant encouragement were an inspiration.

SUMMARY

The inherent economy of utilizing locally available materials in the construction of modern highway systems has placed emphasis on the modification of these materials to meet present and future construction requirements. Modification of a soil to meet certain specifications can be achieved by the addition of a stabilizing agent that will enhance the desirable characteristics of the soil while minimizing the adverse effects from its use.

The objective of the research reported herein was to determine the susceptibility of widely varying soil types to stabilization by the addition of a bituminous material. Selected for use in this study were nine representative soils located in the State of Georgia. The bituminous material chosen as a stabilizing agent was a cutback asphalt, RC-3.

Each of the nine selected soils was combined with RC-3 in increments of 2, 4 and 6 per cent total cutback asphalt by weight of dry soil.

For each of the previously mentioned combinations of materials, moisture-density relationships were determined by the Standard Proctor Test (AASHO designation - T-99-57). The addition of cutback asphalt to a well graded soil caused an increase in density as compared to the density of the soil proper. On the other hand, combining RC-3 with a uniformly graded soil caused a decrease in density.

By utilizing values obtained from the moisture-density tests, triaxial shear strength specimens 2.8 inches in diameter and 5.6 inches in height were statically compacted to both maximum density and optimum

moisture content and to densities less than maximum with corresponding moisture contents. The purpose in compacting samples at less than maximum density was to investigate the relationship existing between density and shear strength in bituminous stabilized soil materials.

After compaction and prior to testing, triaxial shear strength specimens were sealed in polyethylene bags and stored at room temperature for one week. Strength evaluations were made from unconfined compressive strength tests and triaxial shear strength tests with a lateral pressure of 20 psi.

In combining the materials it was evident that most intimate mixing of soil and RC-3 occurred at a moisture content at or near optimum moisture content.

The addition of cutback asphalt to the soils used in this research did not materially increase the strength parameters of these soils. However, it can be concluded from an analysis of the test results that the maximum strength properties of each soil do not necessarily occur at the density and moisture content corresponding to the peak of the moisture density curve.

The asphalt content that had optimum influence on the strength parameters of the soils tested varied but was generally found in the range of 2 to 4 per cent.

CHAPTER I

INTRODUCTION

General.--A spiraling economy linked with an unprecedented commercial and industrial expansion is placing great demands on the natural resources of our nation. In like manner, a rapidly increasing highway building program is draining the supply of quality construction materials that are vital to the roadbuilding industry. The scarcity of good construction materials plus the inherent economy in utilizing locally available materials in the construction of modern highway systems has placed emphasis on the modification of these materials to meet present as well as anticipated specifications. Soil stabilization is an effective way to upgrade an otherwise substandard material.

The late Roy W. Crum, former Director of the Highway Research Board had this to say about soil stabilization;[1*] "A stabilized fill, subgrade, road surface or road base is one that will stay put and stabilization is the process that made it that way." The author does not attempt to improve on this statement but only to further define soil stabilization as that process, either chemical or mechanical that alters the engineering properties of a soil in such a manner as to render the material suitable as an integral portion of the highway structure.

Early forms of soil stabilization were simple. The compaction of a fill increased the density of the material, decreased the water sensitivity

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* Numbers refer to bibliography.

and rendered the fill more stable. On the other hand, technological advances introduced more complex forms of soil stabilization such as blending the soil with an admixture, a process requiring special equipment and skilled personnel. Whether the stabilization procedure is simple or complex, it is nevertheless essential in many situations in order to provide adequate highway systems consistent with economy.

Bituminous soil-stabilization.--On a typical highway construction project, many widely varying soil types are likely to be encountered. Consequently, a desirable characteristic of a stabilizing process or type of admixture would be the ability to benefit the engineering properties of different soil types.

Cutback asphalt is an asphalt cement that has been liquefied by blending with petroleum diluents. Upon exposure to atmospheric conditions, the diluents evaporate leaving the asphalt cement as a residue. This base asphalt has two characteristics, both of which may be beneficial in soil stabilization. Asphalt cement acts to some degree as a cementing agent thereby introducing cohesion to granular materials and increasing the stability of the combined materials. On the other hand asphalt cement is a waterproofing agent that can render water sensitive soils stable by preventing the intrusion of moisture.

The object of this research is to evaluate the factors influencing the soil-water-cutback asphalt stabilization mechanism and to develop a laboratory procedure for the design and control of bituminous stabilized bases and subgrades.

Several representative soil types found in the state of Georgia were selected to determine the susceptibility of these soils to stabilization by the addition of a bituminous material. These different soil types were combined with cutback asphalt to determine the optimum asphalt content for each soil. In order to achieve maximum resisting characteristics from the soil-water-cutback asphalt mixture it was necessary to determine:

1) the moisture-density relationships of the materials involved that coincides with maximum strength.
2) the effectiveness of cutback asphalt as a "lubricant" in compaction.
3) the correct mixing, curing, compaction and strength testing cycle.

The triaxial shear test was chosen as the criteria for evaluating stability soil-water-cutback-asphalt mixtures for the following reasons:

1) The desired result of a stabilization process is an increase in stability. Compressive strength as evidenced in a triaxial shear test is a measure of stability.
2) The triaxial shear test is a familiar laboratory procedure that does not require special equipment other than that normally found in a soil testing laboratory.
3) The merits of other admixtures have been judged by this test and correlation with research of this nature will be provided.

At the recommendation of the Georgia Highway Department RC-3 was selected as the cutback asphalt to be used in this investigation.

Previous research in bituminous soil stabilization.--Full scale tests incorporated in a correlation study by Endersby[2] indicated the presence of high confining pressures imposed through paving restraint. This paving restraint, according to Endersby gave rise to higher stability values as compared to similar soil-cutback asphalt mixtures tested in the laboratory.

Prandtl[3] devised a bearing power test that introduced the effects of paving restraint as well as measuring the values of cohesion and internal friction. Comparing the results of his bearing power test with results of unconfined compressive tests Prandtl reported values of bearing power ten times that of unconfined compressive strength. The fact that full size pavement sections contribute confining pressures in excess of those imposed on laboratory samples has been evidenced in existing bases and subgrades that have performed satisfactorily despite laboratory tests indicating insufficient stability.

The preceding information indicates a need for research in stress distribution beneath various types of surface and base materials.

In all probability, the most argumentative aspect of bituminous stabilization is the relationship between moisture and cutback asphalt in the compaction characteristics of bituminous stabilized materials. Cutback asphalt is composed of asphalt cement and a gasoline or naptha diluent, the volatility of which depends on the particular grade. The volatiles present in cutback asphalt serve to some extent as a lubricating medium in compaction in much the same manner as water. Whether one percent volatiles exhibits the same effect on the compaction characteristics of a particular soil as one percent water is a much discussed topic with widely varying theories represented.[4,5]

The American Road Builder's Association[6] makes the following suggestions as to the physical characteristics of the soil material that is to be stabilized with cutback asphalt:

1) Per cent passing a No. 4 Sieve $\geq$ 50.

2) Per cent passing a No. 40 Sieve, 50-100.

3) Per cent passing a No. 200 Sieve $\leq$ 35.

4) Liquid limit should be less than 30%.

5) Plasticity index must be less than 10.

The effects on density and strength of compacted mixtures appears to depend on the gradation characteristics of a soil. The principal function of asphalt in a cohesive soil is to waterproof the consolidated soil mass. Findings such as these are reported in a paper prepared by Puzinauskas and Kallas.[7]

CHAPTER II

DESCRIPTION OF MATERIALS AND LABORATORY TEST EQUIPMENT

Soils.--Located within the State of Georgia are an estimated[8] 25 major soil types. Each one of these major soil types may be subdivided into what would eventually amount to an infinite variety of soil conditions that vary geographically throughout the state.

This particular phase of soil stabilization is a portion of a long-range program to evaluate the susceptibility of various Georgia soil types to stabilization by different admixtures.[8] Originally, nine soil types were selected for this program. In order to afford a comparison with previous work of this nature, these same soils were utilized in this research. The criteria for selecting representative soils was the frequency of which the soil was encountered in highway construction as well as the characteristics of the material that necessitated stabilization.

As the laboratory supply of a particular soil was depleted it was necessary to return to the original source for additional material. Often the original source of a soil was a county or state borrow pit that was no longer in use. Hence, exact duplication of a particular soil type was difficult if not impossible. This situation is explained in order to justify inconsistencies in the physical characteristics of the soils reported herein and those soils corresponding to previous research in this program.

A detailed description of the physical characteristics of each soil is presented in Table 1, and the gradation curves appear in Fig. 1 and Fig. 2. The geographical location of each soil is shown in Fig. 3.

Table 1. Location and Description of Soils in Georgia

Soil No.	I	II	III	IV	VI	VII	VIII	IX
Location (County)	Carroll	Effingham	Camden	Fulton	Gordon	Clayton	Putnam	Putnam
Gradation Per Cent Passing U. S. Standard Sieve Shown								
Sieve No. 10	97	100	100	97	76	99	98	99
Sieve No. 40	86	46	98	81	51	70	93	94
Sieve No. 60	63	32	93	72	48	63	89	86
Sieve No. 100	56	26	47	63	46	44	85	76
Sieve No. 200	38	17	8	54	44	39	83	70
% Silt	21	2	3	22	7	23	20	31
% Clay	6	11	--	27	31	16	60	33
Liquid Limit	13	14	--	29	20	24	64	47
Plastic Limit	--	--	--	23	--	14	48	44
Plasticity Index	NP	NP	NP	6	NP	10	16	3
Specific Gravity	2.67	2.63	2.69	2.70	2.67	2.59	2.67	2.63
AASHO Classification	A-4-(0)	A-2-4(0)	A-3-(0)	A-4-(4)	A-1-a(0)	A-4-(0)	A-7-5(15)	A-5(8)
GHD Classification	C-1 Topsoil	A-1 Topsoil	A-1 Subgrade	I-B Embankment	A Chert	B-11 Subgrade	III-B Embankment	II-A Embankment

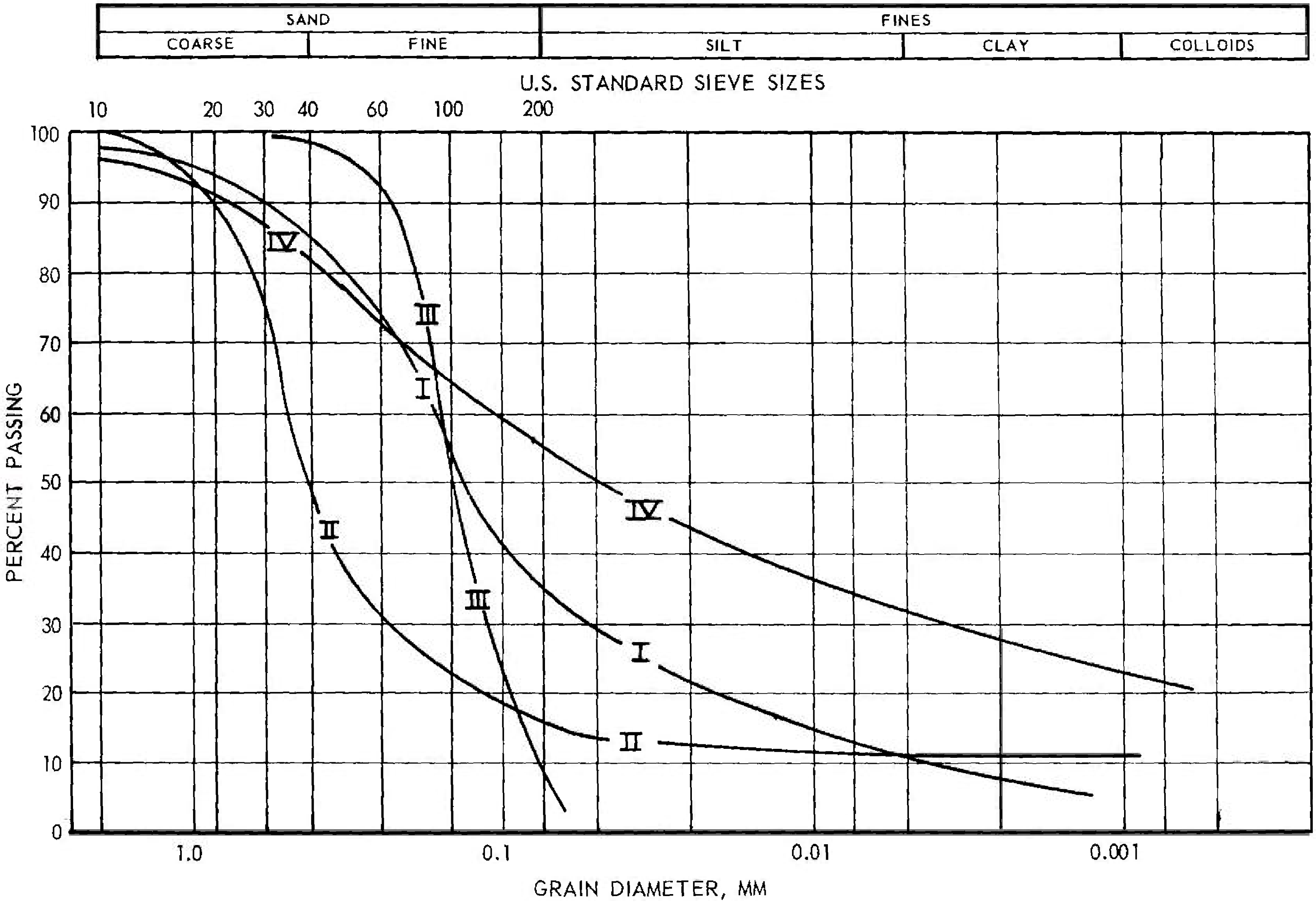

Figure 1. Gradation Curves for Soils I, II, III and IV.

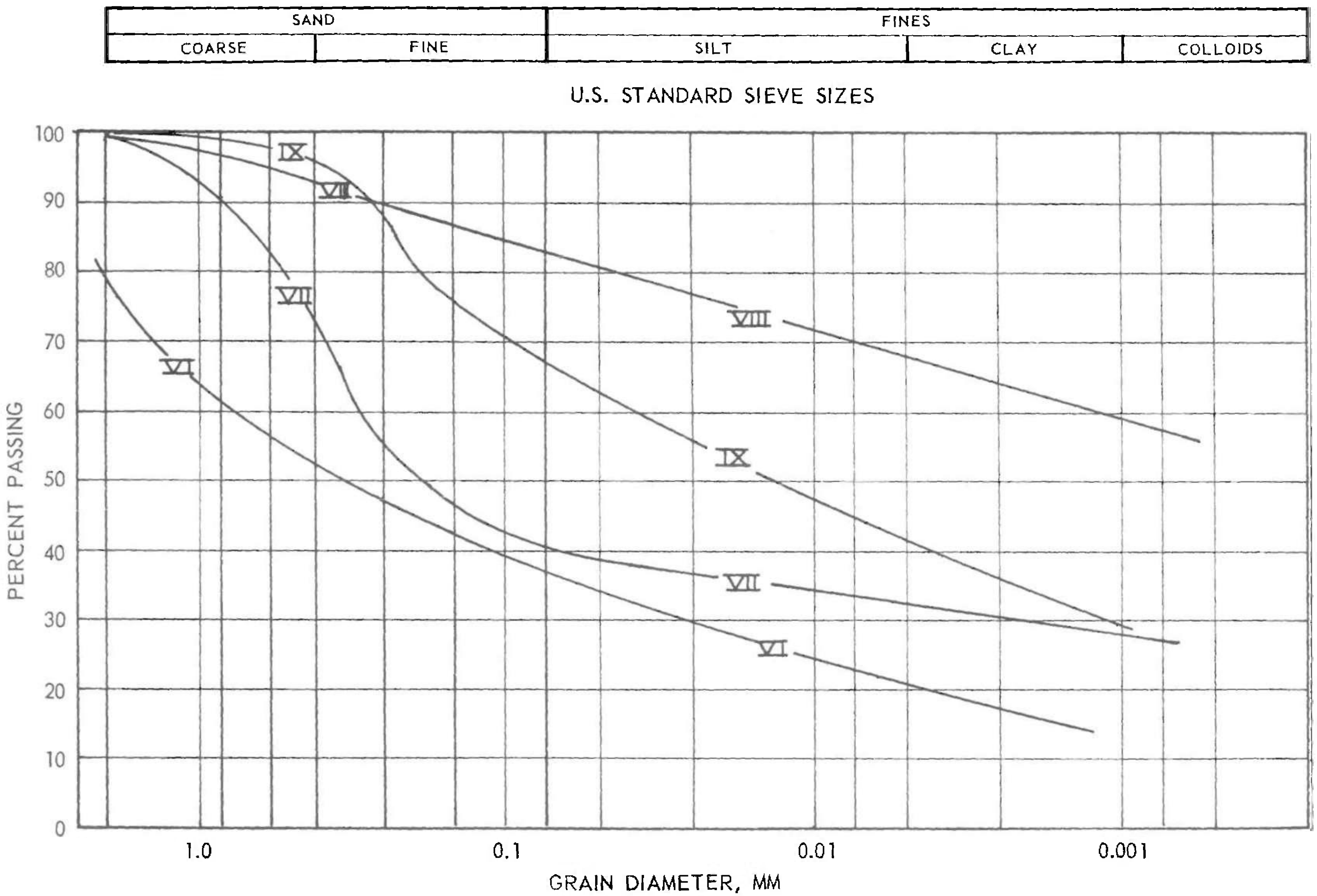

Figure 2. Gradation Curves for Soils VI, VII, VIII and IX.

Figure 3. Sketch Map, State of Georgia, Showing Soil Locations.

All soil classification tests to identify these soils conform to standard recommended practices of the American Association of State Highway Officials as well as recommendations in soils testing manuals.[9]

Soil I is a moderately well graded, non-plastic, yellow-brown, silty sand. Soil II is a uniform, non-plastic, red-brown, silty sand. Soil III is a uniform, grey-to-black beach sand. Soil IV is a well-graded, non-plastic, yellow-brown, silty sand. Soil VII is a well-graded, brown, silty, clayey sand of medium plasticity. Soil VIII is a plastic, deep red, silty clay containing a large amount of mica flakes. Soil IX is a well-graded, red-brown, sandy, silty, clay of moderate plasticity.

Cutback asphalt (RC-3).--Rapid curing cutback asphalt (RC-3) is an asphalt cement (AC-8) that has been liquefied by blending with petroleum dilutents of high volatility such as naptha or gasoline.

The RC-3 utilized in this research was supplied by the Savannah, Georgia Refinery of the American Oil Company. The following is a typical chemical analysis of this material:

Flash Point (Open Tag)............95°
Saybolt Viscosity at 140° F.......438

Distillation Test:
Distillate, percentage by volume of total distillate:
- 374° F.........................19%
- 437° F.........................60
- 500° F.........................76
- 600° F.........................91

Residue from distillation to 680° F.........................79%
Specific Gravity at 60° F......... .9759
Residue Penetration at 77° F......90
Ductility at 77° F................100+
Solubility in CCl_4...............99.9%
Spot test........................Negative

Mixing equipment.--The three constituents of the mixture (soil, water, RC-3) were blended with a Hobart C-100 mixer equipped with a flat blade. The mixture was blended at a speed of 144 revolutions per minute. After mixing, the blended material was aerated in 12 x 24 x 3 in. metal trays. Air was circulated across these trays using an Emerson Electric fan with a 16 in. blade. These two items of equipment are shown in use in Fig. 9.

Before and after mixing, as well as during the aeration process, approximate moisture contents were taken with a Speedy Moisture Tester manufactured by the Alpha-Lux Company. More accurate moisture contents were determined by oven-drying samples at 110° C for 24 hours.

Compaction equipment.--Moisture density relationships were determined by the Standard Proctor compaction test, AASHO designation, T-99-57. This test utilizes a compaction mold with a volume of 1/30 cu. ft. A compactive effort of a 5.5 lb. ram with a 12 in. stroke is applied 25 times to each of three equal layers.

Triaxial test cylinders were compacted in an 8 in. length of steel tube reamed to an inside diameter of 2.8 in. To afford compaction at the top and bottom of the cylinders, two soft aluminum pistons working toward each other were utilized. Spacer clips were positioned around the bottom piston to support the tube prior to application of compaction forces. With the application of the compactive forces these spacer clips were removed to allow vertical movement of the bottom piston. The height of sample was controlled by an Ames dial attached to a 12 in. length of aluminum angle. The source of compaction effort for making triaxial test cylinders was a Tinius-Olsen 120,000 lb. capacity, controlled-strain, hydraulic testing machine. Fig. 4 shows a triaxial test specimen being compacted. The rate of strain was .035 inches per minute.

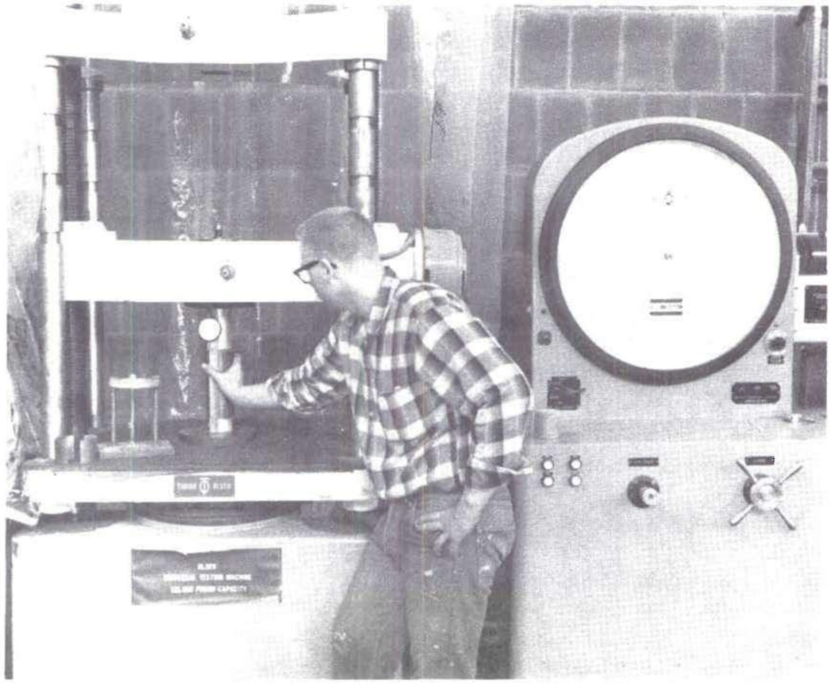

Figure 4. Compaction of Triaxial Shear Strength Samples.

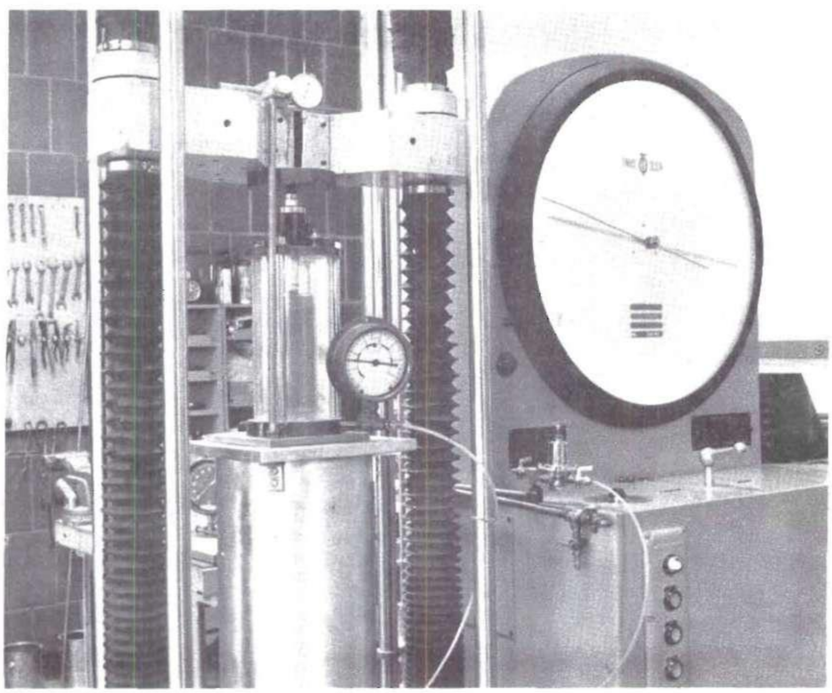

Figure 5. Triaxial Shear Test in Progress.

Triaxial test equipment.--A Tinius-Olsen, 20,000 lb. capacity constant-strain, electric testing machine was used to perform the triaxial shear test. Lateral pressures were applied by compressed air. Test cylinders were placed in an air-tight plexiglass cylinder. Load transfer from the testing machine to the cylinder was accomplished by a 3/4 in. diameter steel piston. Fig. 5 illustrates a triaxial shear test in progress. The rate of strain was .075 inches per minute.

CHAPTER III

DEVELOPMENT OF LABORATORY DESIGN PROCEDURES

General.--The impetus for research of this nature is the application of laboratory results to the construction of modern highway systems. Two outstanding principles must be adhered to in order to present to the highway construction industry factual information of a usable nature. In the same manner that a Standard Proctor compaction test simulates a compactive effort generated by heavy construction equipment, each phase of a laboratory testing program must be conceived so as to be readily reproduced by existing equipment and techniques of construction. Secondly, the predominating variables of the materials involved must be determined and a satisfactory method for evaluating these variables must be the basis for development of a laboratory design procedure.

Soil identification and classification.--As each soil was received in the laboratory it was placed in large, shallow pans and allowed to air-dry. After air-drying the material was passed through a No. 4 sieve with all material retained on the No. 4 sieve discarded.

The following physical tests were run on material passing the No. 4 sieve of each soil for identification and classification:

1) Atterberg limits

   a. Plastic limit
   b. Liquid limit
   c. Plasticity index

2) Specific Gravity

3) Grain size distribution

a. Mechanical analysis
b. Hydrometer analysis if required

4) Standard Proctor compaction test (See Table 2)

Tabular results of all physical tests are presented in Table 1.

Moisture-Density relationships.--The final structural arrangement of a soil that has been subjected to a certain compactive effort is a function of many variables. Four of these variables that have the most pronounced influence are: 1) grain size and shape, 2) the frequency of appearance of a particular grain size, (gradation), 3) the moisture content of the soil at the time of compaction, 4) plasticity characteristics of clay.

The grain size and shape and the gradation determine the number and size of voids within the compacted soil. On the other hand, moisture serves to overcome frictional resistance generated between particles thereby making a more intimate grain contact possible. At the same time, moisture will increase the unit weight of the material by filling a portion of the otherwise weightless air voids.

For a given compactive effort there is a condition at which a state of maximum density will occur. Corresponding to this maximum density is a moisture content that best fulfills the dual role described in the preceding paragraph. Since this moisture content has distinct significance as related to maximum density, it is termed optimum moisture content and abbreviated OMC.

If the basic ingredients of the compaction process are altered, as is the case when a stabilizing admixture is incorporated, certain changes in the compaction characteristics of the new material are to be anticipated.

The exact way in which the compactive characteristics are altered will depend on the type of stabilizing admixture utilized. On the one hand, a dry, fine-grained admixture, such as Portland cement, may increase OMC due to the large surface area of material of this nature. At the same time, filling voids in the compacted mass with a material of relatively high specific gravity will increase maximum density to some degree. On the other hand, a liquid admixture may act as a lubricating medium thus reducing the moisture requirements of the soil at maximum density.

This research is concerned with the stabilization of various soil types with a cutback asphalt, RC-3. RC-3 is a two phase material consisting of a base asphalt cement (AC-8), and a petroleum diluent such as gasoline or naptha.

The effect of cutback asphalt on the compaction characteristics of a soil is a controversial subject. This controversy stems from the widely varying theories as to the actual part that the diluents in cutback asphalt play in replacing moisture as a compaction lubricant.

To develop some insight into this question, a Standard Proctor compaction test was run on a dry soil combined with various percentages of RC-3. Graphical representation of dry density versus cutback asphalt content resulted in a curve similar to a moisture density curve. As seen in Figures 6A and 6B the maximum density of the dry soil and cutback asphalt combination was approximately 92 per cent of the maximum density achieved from a regular moisture-density test on this particular soil. From a quantitative standpoint this curve tends to prove that cutback asphalt has an important role as a lubricant in compaction.

To further investigate the soil-water-cutback asphalt compaction phenomenon it is necessary to define certain basic relationships of the

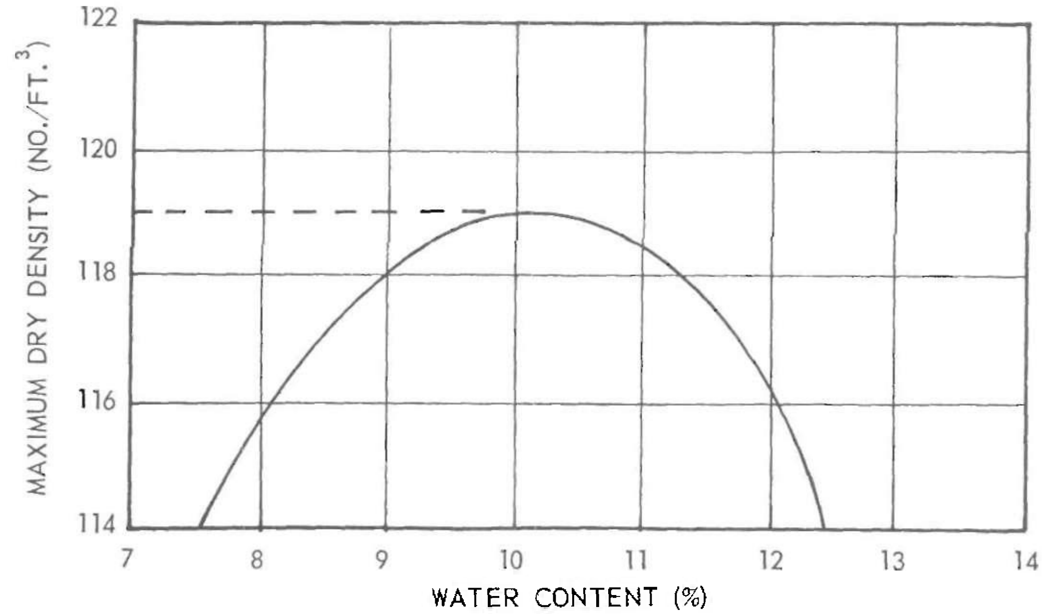

Figure 6-A. Maxium Dry Density Vs. Water Content, Soil II.

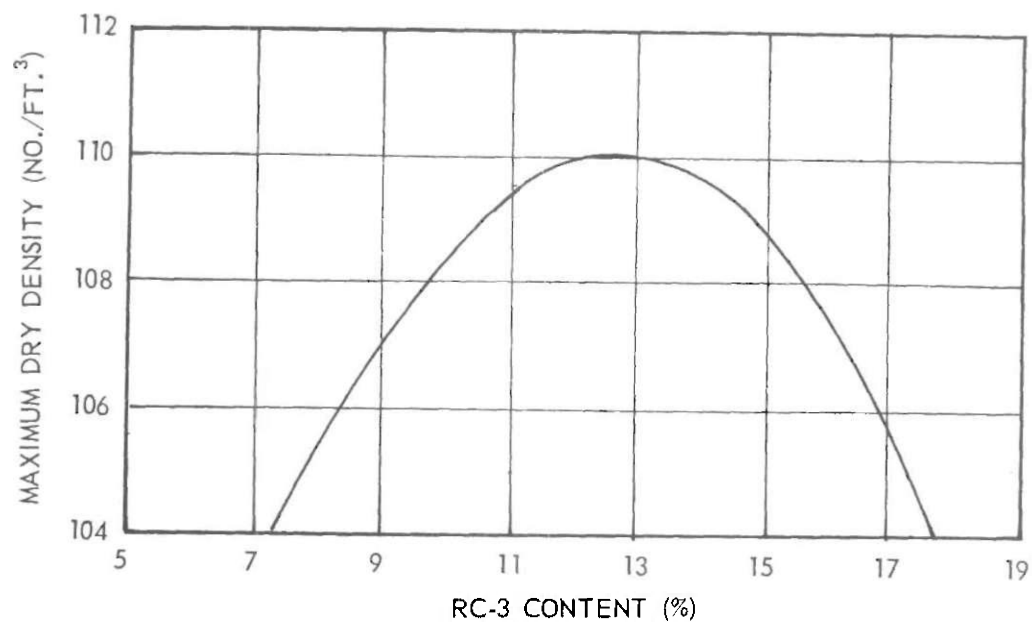

Figure 6-B. Maxium Dry Density Vs. RC-3 Content, Soil II.

materials involved. First of all, RC-3 is approximately 80 per cent solid asphalt and 20 per cent liquid diluent by volume. The weight relationships are similar to this; 85 per cent solid asphalt and 15 per cent liquid diluent.

The importance of the weight relationship is evidenced in the following definitions:

W_w = Weight of Water

W_s = Weight of Soil Solids

W_d = Weight of Diluent

W_a = Weight of Solid Asphalt

Water Content (W.C.) $= \dfrac{Ww}{Ws}$

Liquid Content (L.C.) $= \dfrac{Ww + Wd}{Ws + Wa}$

Water content as defined above is a popularly accepted definition and can be readily used if soil and water are the only constituents of the mixture. However, when soil, water and cutback asphalt are combined, and a "moisture" sample taken from this mixture, then the procedure for determining water content will actually yield liquid content as defined above. Further complicating the problem is the fact that the amount of diluents present at a given time is a function of previous exposure and agitation while the amount of base asphalt will remain constant.

The overall complexity of the problem can be evidenced from a comparison of the compaction test of a soil-water mixture and a soil-water-cutback asphalt mixture.

The procedure for determining compaction characteristics of a soil-water mixture is to apply a certain compactive effort to various proportions of soil and water ranging from a relatively dry condition to a distinctly wet condition. For each proportion of soil and water, a representative sample is placed in an oven and allowed to dry. Water content is then determined by the preceding relationship. A graphical representation of dry density versus water content is made and from this curve the maximum dry density of the material and the water content (OMC) that yielded this density is selected. This is a straightforward process in which the relationship between soil density and moisture content is well defined.

The mechanics of determining compaction characteristics of a soil-water-cutback asphalt mixture is similar to that described above. However, when a sample of the material is placed in an oven and allowed to dry, liquid content rather than moisture content is determined since weight loss is attributable to evaporation of water and diluents; the solid residue consists of both soil solids and base asphalt.

To theoretically describe the exact relationship of soil-water-cutback asphalt compaction characteristics is impractical for the following reasons:

1. Cutback asphalt is manufactured according to minimum standards and the weight and volume relationships will vary from this minimum.

2. The amount of diluents reamining in the liquid asphalt decreases with exposure to evaporation and with agitation due to mixing.

To practically describe the overall effect of the soil-water-cutback asphalt compaction process is possible and can be evidenced from the following example:

Combine 10 lbs. of dry soil with 1.0 lb. of water so that the water content equals 10 per cent. To this add 6 per cent cutback asphalt by weight of dry soil. From this mixture, remove a representative sample and determine the liquid content by oven drying. Assume that the liquid content equaled 10.5 per cent. Now, the water content of the soil was dependent on the original proportions of soil and water and was in this case equal to 10 per cent. The difference between the liquid content, 10.5 per cent, and the water content, 10 per cent, is the measured effect of the cutback-asphalt in the moisture-density relationships. A series of simple tests indicated that this difference is a constant for a given percentage of cutback asphalt regardless of the water content of the soil.

In the compaction test of a soil-water-cutback asphalt mixture, the optimum liquid content can be determined graphically. The correction factor can be applied to this optimum liquid content, resulting in the optimum moisture content of the soil proper.

Optimum moisture content for a soil-water-cutback asphalt mixture can be defined as the required moisture content of the soil so that maximum density will occur when the soil is compacted in the presence of a given percentage of cutback asphalt.

<u>Moisture-Density tests</u>.--The equipment used, and the general procedure followed in the moisture-density tests conform to the Standard Proctor Compaction Test, AASHO designation T-99-57.

For each point on the moisture-density curve five lbs. of dry soil were combined with a predetermined amount of water. Next, the correct increment of cutback asphalt was combined with the soil and water and mixed thoroughly. The prescribed compaction effort was applied, wet density determined and a representative sample of the mixture was placed in an oven at 110° C for 24 hours for liquid content determination. The liquid content of each test point was then compared to the water content of the same test points so as to determine the correction factor relating liquid and water contents for this particular soil and increment of cutback asphalt. Optimum moisture content of the soil was found by applying the correction factor to the liquid content corresponding to maximum dry density.

Effect of moisture content and density on triaxial shear strength.--The preceding section of this chapter dealt with the establishment of moisture density relationships of soil-water-cutback asphalt mixtures. The application of moisture-density information is essential to proper proportioning of materials for strength evaluation.

In order to obtain a condition of maximum density a certain amount of moisture was required for lubrication of the individual particles. This moisture that is necessary in compaction may well be detrimental in strength evaluation by reducing frictional resistance between grains and, consequently, reducing the shear strength of the material. Or, in other words, maximum strength characteristics may not be coincident with maximum density characteristics.

To determine the effect of moisture content on strength, a series of cylinders were compacted to maximum density at optimum moisture content. After compaction, these cylinders were subjected to various drying efforts ranging from complete moisture loss to complete moisture retention. It is evident from the curve in Figure 7 that triaxial shear strength increases as moisture content decreases. Hence, any legitimate means for the removal of moisture after compaction would enhance the strength characteristics of the stabilized material involved. Conversely, the intrusion of moisture into a stabilized layer after compaction could prove detrimental from a load resisting standpoint.

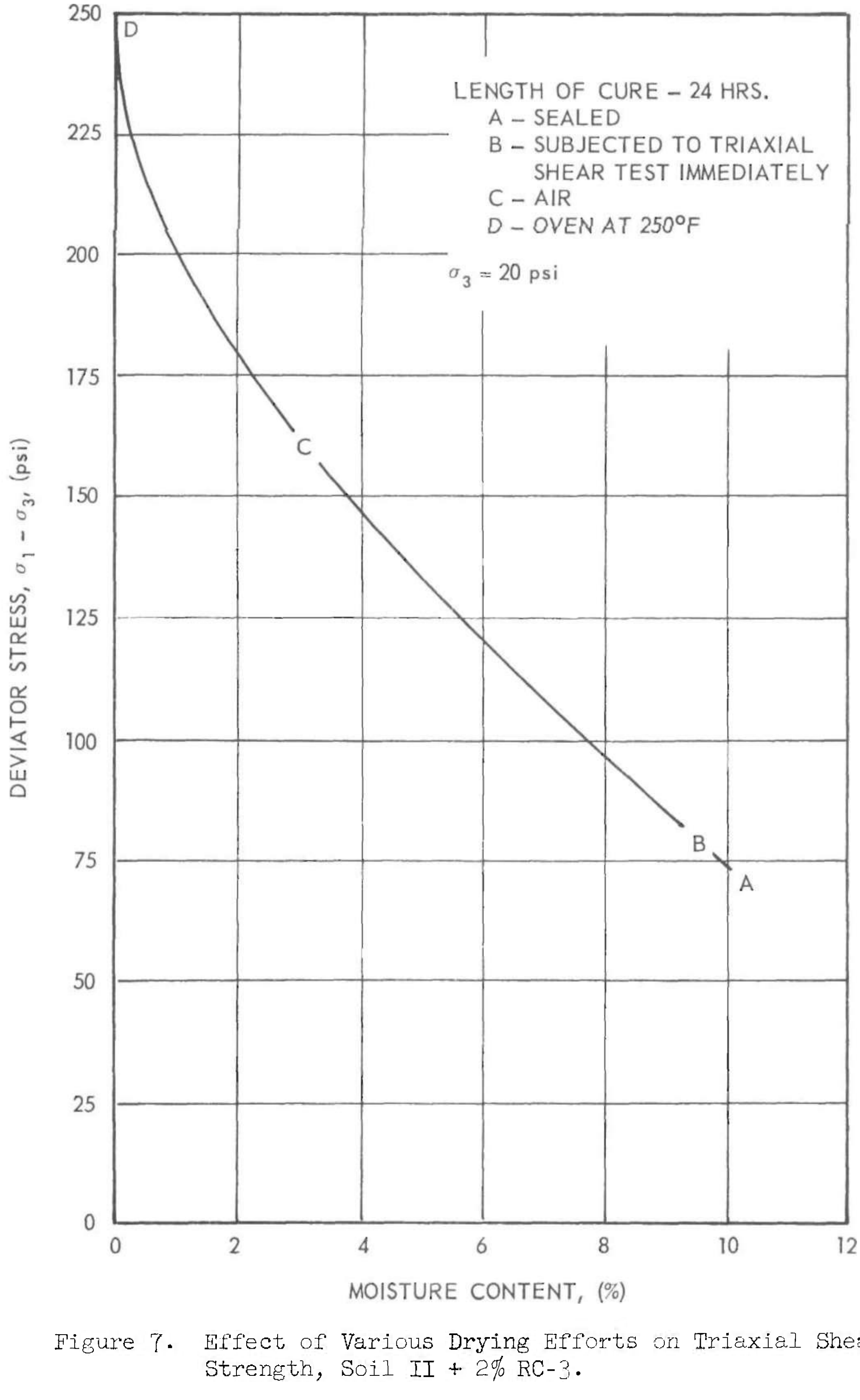

Figure 7. Effect of Various Drying Efforts on Triaxial Shear Strength, Soil II + 2% RC-3.

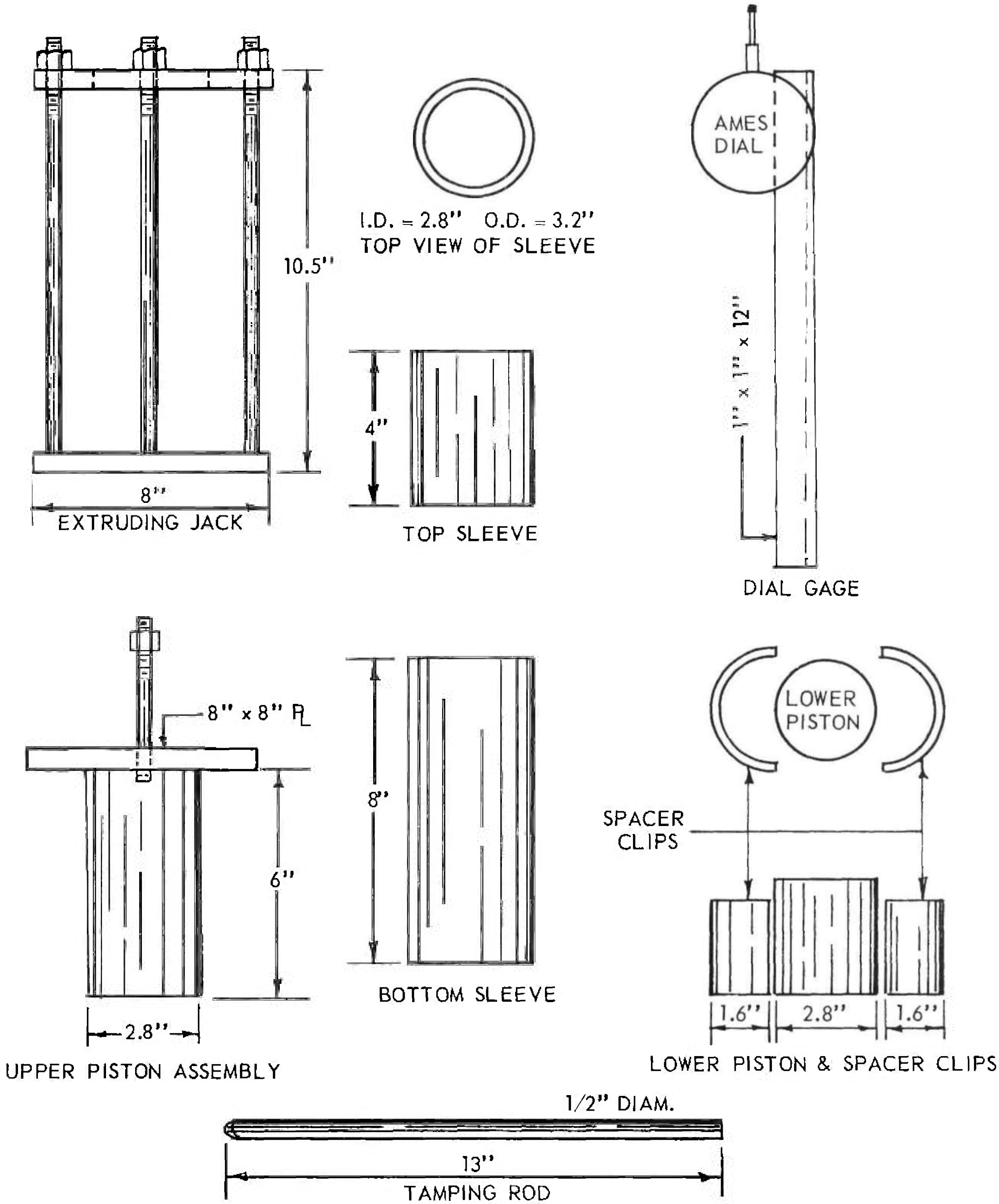

Figure 8. Triaxial Shear Sample Compaction Equipment.

Unfortunately, modern construction practices preclude moisture loss after compaction. Only a small portion of the compacted material is exposed and the length of exposure is short due to the application of other components of the roadway system. Consequently, moisture and diluents present at compaction will be trapped in the final compacted layer of material.

A means of circumventing this situation would be to minimize the moisture present at compaction by:

1) Mixing soil and cutback asphalt at a moisture content less than OMC.

2) Mixing soil and cutback asphalt at a moisture content equal to or near OMC and allowing the mixture to "dry back" prior to compaction.

Of the two alternatives suggested above, the second is the most feasible. In the majority of the soils tested in this research, the most intimate mixing of RC-3 and soil occurred at a moisture content very close to optimum. Secondly, a portion of the diluents present in RC-3 are allowed to volatilize during this "dry-back" stage.

The shape of a moisture-density curve indicates that for a decrease in moisture content, there is a corresponding reduction in density. This reduction in density occurs because, no longer is there sufficient moisture to fill the voids within the compacted mass and to provide a lubricating medium between particles. A reduction in density would, intuitively, bring about a reduction in shear strength.

Does the increased shear strength from a reduction in moisture content more than offset the anticipated loss in shear strength resulting from a decrease in density? The answer to this question was the nucleus around which the laboratory design procedure was formed for evaluating the shear strength characteristics of bituminous stabilized bases and subgrades. This argument is based on the premise that proper drainage is provided during and after construction and no major increases in moisture content due to capillarity are anticipated.

<u>Mixing and compaction of triaxial shear strength cylinders</u>.--RC-3 was added to each soil in increments of 2, 4 and 6 per cent total cutback asphalt by weight of dry soil. Consideration was given to heating the RC-3 prior to mixing with the soil. However, when hot cutback asphalt was introduced to a soil at room temperature, the mixture would coagulate before thorough mixing was accomplished. Consequently, soil and RC-3 were combined at room temperature to facilitate the distribution of cutback asphalt within the soil material.

Several sequences of mixing were investigated. Optimum results were obtained by simultaneously introducing RC-3 and water to the soil. At the time of introduction, the air-dry soil was being agitated by the mixer at a speed of 144 revolutions per minute. Mixing was then continued at this speed with frequent stops to remove material from the beater and to prevent caking around the sides of the mixing bowl. Total elapsed time for the mixing phase was 10 minutes.

<u>Maximum stage samples</u>.--Maximum stage samples as referred to here, are the triaxial shear strength specimens that were compacted at a density and moisture content equal to the maximum density and optimum moisture content as obtained from the Standard Proctor compaction test.

An amount of material sufficient to make four cylinders, 2.8 inches in diameter and 5.6 inches in height was mixed as previously described. After mixing, maximum stage samples were ready for compaction. The spacer clips are positioned around the lower piston (See Figure 8). The lower sleeve was then placed on top of the spacer clips. The relative dimensions of the spacer clips and lower piston are such that the lower piston will protude into the lower sleeve. At this point, approximately one-third of the pre-mixed material required for one sample was placed in the lower sleeve and rodded lightly with 20 strokes of the tamping rod. The purpose of this rodding is two-fold. First of all, horizontal shear planes developed by static compaction are reduced. Secondly, once this portion of the material has been rodded the spacer clips can be removed with frictional resistance alone supporting the lower sleeve. The remaining material required for one sample was then placed in the lower sleeve, rodded as before and positioned under the upper piston assembly.

Compaction force was supplied through the hydraulic system of a 120,000 lb. controlled strain testing machine pictured in Figure 4. The rate of strain was .035 inches per minute. With the spacer clips removed both pistons are free to move in a vertical plane thus providing compaction from the top and bottom of the sample simultaneously. The total amount of material placed in the lower sleeve was such that when the upper and lower pistons were 5.6 inches apart, the material between these pistons would be compacted to the desired density.

After compaction the lower sleeve was placed on the extruding jack. The upper piston forced the compacted cylinder down and out from the lower sleeve; a sample identification tag was attached and the cylinder sealed in a polyethylene freezer bag. During compaction, two representative samples were taken for moisture content determination.

Dry-back stage samples.--Dry-back stage samples as referred to here are the triaxial shear strength specimens that are compacted on the "dry" side of the moisture-density curve as obtained from the Standard Proctor compaction test. If the quantity of soil permitted, two dry-back stages were compacted for each of the maximum stages. This system afforded a total of three shear strength determinations for each combination of soil and RC-3.

The procedure for compacting dry-back stage samples was very similar to the procedure described for the compaction of maximum stage samples. However, an extra five lbs. of material was added at mixing so that in addition to the material required for four samples there was sufficient material for one test point of the Standard Proctor compaction test.

After mixing, the material was placed in 12 x 24 x 3 inch metal trays. Air was circulated across these trays by an electric fan as seen on Figure 9. At the same time the mixture was stirred constantly with a small trowel so as to avoid non-uniform drying. The length of time of this aeration process is dependent on the desired moisture content at compaction, i.e., the desired dry-back stage. The length of time required to obtain a particular moisture content is a function of the soil type and cutback asphalt content; clayey materials are reluctant to give up moisture and require more time for aeration; high asphalt contents also inhibit moisture loss. The best guide as to length of aeration is familiarity with the materials involved. However, on the spot moisture approximations utilizing the Speedy Moisture Tester serve a useful purpose along this line.

If the exact value of the moisture content were known at the termination of the dry-back stage, this value could be compared to a moisture-density curve and the appropriate density selected for compaction. Although accurate moisture content determination is a simple procedure, it is time

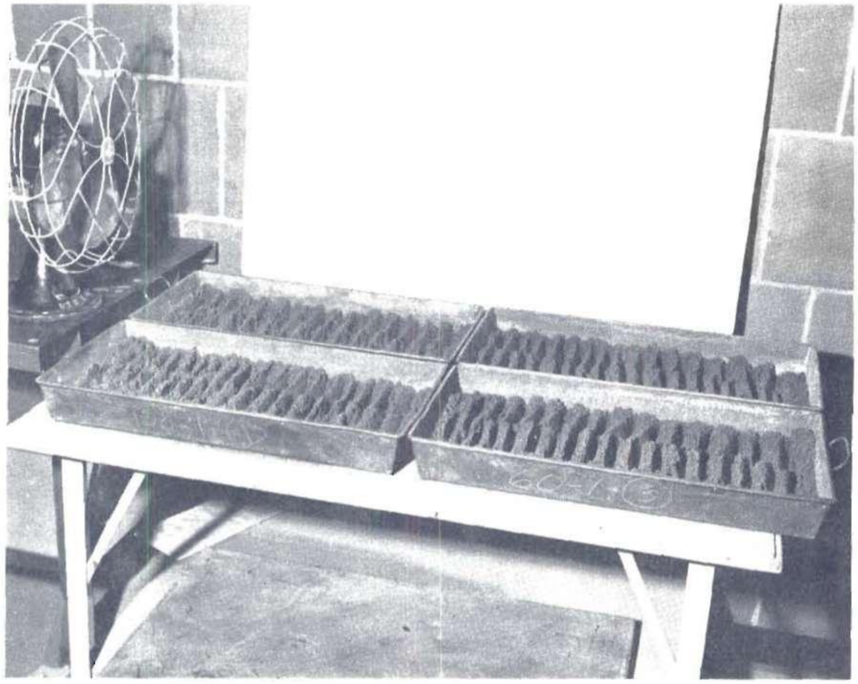

Figure 9. Aeration of Soil Bituminous Mixtures Prior to Compaction.

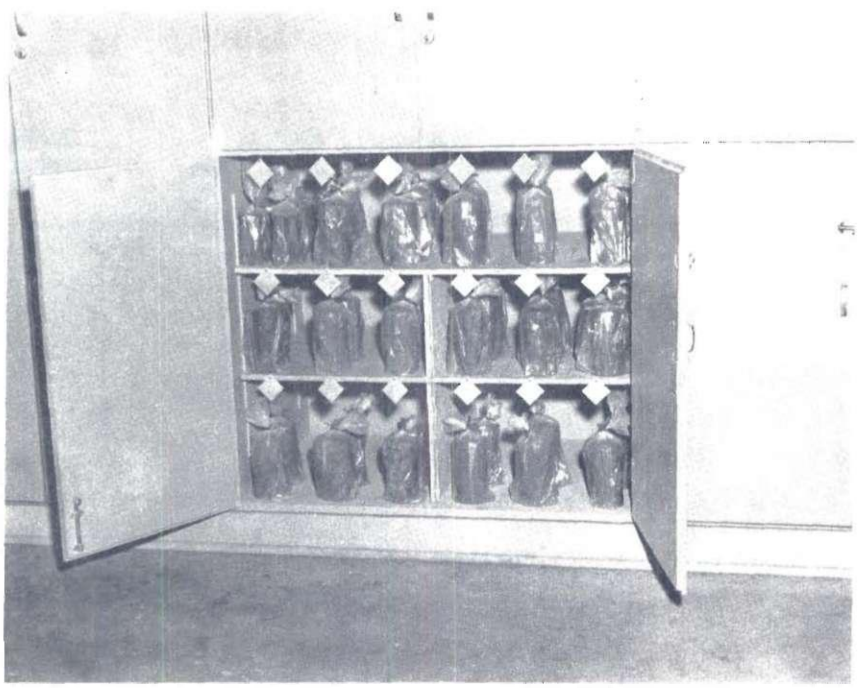

Figure 10. Storage Cabinet for Triaxial Shear Strength Specimens.

consuming and would cause untimely delays. Therefore, a Standard Proctor Compaction test is run on the material to determine the correct density corresponding to the moisture content at termination of the dry-back stage.

The procedure for compaction of triaxial shear strength samples in a dry-back stage was the same as that described under maximum stage samples.

Curing.--A stabilized base or subgrade in a modern highway construction project is only one component of many constituting the final cross-section. It can be reasoned from this that time is of essence in curing stabilized bases and subgrades so as to allow the application of the remaining components of the highway structure. Applying one of these components such as a concrete or bituminous wearing course virtually seals the stabilized material from exposure to the elements, with the exception of normal fluctuations of ground water.

In keeping with a principle discussed in the beginning of this chapter, the curing effort applied to test specimens in this research was selected so as to closely approximate the construction techniques of field curing. After compaction, triaxial shear strength samples were sealed in polyethylene freezer bags so as to minimize moisture loss. These sealed samples were then stored in a cabinet for a period of 7 days. The function of this 7 day period was to facilitate orderly scheduling of laboratory work.

No attempt was made to regulate temperature or humidity within the storage cabinet. The curing cabinet complete with triaxial shear strength samples is shown in Fig. 10.

Triaxial shear strength testing.--Confined and unconfined compressive strength evaluations were made on each soil and each test increment of RC-3 for both maximum and dry-back stages. Lateral pressure equal to 20 psi was developed by introducing compressed air into a sealed plexiglass cylinder. Thin rubber membranes were placed around confined compressive strength samples.

Strain measurements were recorded in increments of .025 inches using an Ames dial attached to the triaxial cell.

The rate of loading corresponded to 0.75 inches per minute of vertical head travel. After completion of the triaxial shear test a moisture content sample was removed from each test cylinder.

Fig. 5 shows a triaxial shear test in progress.

CHAPTER IV

EVALUATION OF TEST RESULTS

General.--It was the intention of the preceding laboratory testing procedure to make optimum use of RC-3 as a stabilizing admixture for soil construction. The criteria upon which the merits of this admixture were evaluated was primarily compressive strength data. No doubt there are beneficial characteristics of cutback asphalt such as waterproofing capabilities that are not reflected in results of triaxial shear tests.

Moisture-Density.--The results of the moisture-density determinations are presented in tabular form in Table 2. The information contained in this table includes maximum dry density (M.D.D.), optimum liquid content (O.L.C.) and optimum moisture content (O.M.C.) for each soil combined with 2, 4 and 6 per cent RC-3. Any blank columns in this table indicate an insufficient quantity of material to complete the moisture-density series.

The overall effect of the addition of RC-3 on the moisture-density characteristics of a particular soil can be evidenced in the following summary table.

Soil No.	AASHO Designation	Maximum Dry Density	Optimum Moisture Content
I	(A-4-(0))	decreased	decreased
II	(A-2-4(0))	increased then decreased	increased
III	(A-3-(0))	increased then decreased	increased
IV	(A-4-(4))	decreased	decreased
VI	(A-1-a(0))	decreased	increased
VII	(A-4-(0))	decreased	decreased
VIII	(A-7-5(15))	increased then decreased	constant
IX	(A-5(8))	decreased	constant

Table 2. Maximum Dry Density, Optimum Liquid Content and Optimum Moisture Content for Soils I - IX Combined with 2, 4 and 6% RC-3

RC-3(%)	0		2			4			6		
Soil	M.D.D. #/FT^3	O.M.C. %	M.D.D. #/FT^3	O.L.C. %	O.M.C. %	M.D.D. #/FT^3	O.L.C. %	O.M.C. %	M.D.D. #/FT^3	O.L.C. %	O.M.C. %
I	121.2	12.0	120.0	11.3	10.8	118.4	11.0	10.3	116.6	10.5	9.8
II	119.1	10.3	122.1	10.4	9.9	121.5	9.5	9.0	121.2	8.5	8.0
III	101.0	9.5	104.2	12.0	11.7	106.8	11.0	10.7	--	--	--
IV	114.2	14.6	113.1	14.6	14.2	112.7	13.5	13.0	111.9	13.5	13.0
VI	110.2	14.7	106.8	15.6	15.2	108.4	13.8	13.2	107.5	12.7	12.0
VII	117.4	13.0	113.4	13.5	13.0	112.1	12.5	11.9	110.4	13.5	12.8
VIII	88.7	30.9	91.4	26.1	25.5	92.3	25.8	25.5	90.4	26.5	25.8
IX	100.4	22.4	96.8	23.5	23.0	94.0	24.0	23.5	94.5	23.0	22.6

An inspection of the preceding table indicates that no broad statement can be made concerning the effect of RC-3 on the moisture-density characteristics of a soil material. However, by correlating the variation in maximum density with the gradation characteristics of each soil a significant relationship is obtained. Each soil that increased in density (II, III and VIII) has the same general gradation characteristic (uniformity). A uniform gradation indicates that the majority of the individual particles have much the same size. Therefore, certain particle sizes required to fill voids created by larger particles are lacking. This leads to low densities for uniformly graded materials when compared with well-graded soils. The extent to which this uniformity affects density would depend on the diameter of the uniform particles, with the effect diminishing as particle size decreases.

Hence, any admixture that could serve to fill these voids would in effect contribute to the density of the combination of materials.

Conversely, the addition of cutback asphalt to a well graded material such as Soils I, IV, VI, VII and IX could decrease maximum density by preventing intimate grain contact of soil particles.

In summary, well-graded soils showed a decrease in density while the density of uniformly graded soils was increased by the addition of RC-3.

Confined and unconfined compressive strength results of maximum stage samples.--Maximum stage samples are the triaxial shear strength specimens compacted at a density and moisture content equal to the maximum density and optimum moisture content as obtained from the Standard Proctor compaction test. Any samples that were compacted at a moisture content outside a range of

±1.0 per cent at OMC were rejected. Each strength value recorded represents the average of two samples. In no instance was the deviation between these two strength values of enough significance to warrant rejection.

Confined and unconfined compressive strength values for maximum stage samples are presented in tabular form in Table 3. Graphic illustration of the variation in strength with increasing RC-3 content for maximum stage samples is presented in Figures 11 through 17.

If RC-3 is combined with a soil and compacted at maximum density and optimum moisture content, no strength gains of significance will result. In the majority of soils tested, compressive strength remained constant, or in some cases decreased slightly. The exception to this situation was Soil VIII which showed an increase in strength of 50 per cent when combined with RC-3 and compacted at maximum density and optimum moisture content.

<u>Compressive strength values of dry-back stage samples compared with maximum stage samples</u>.--A comparison of compressive strength values for maximum stage and dry-back samples is presented in Figures 18 through 37. These figures are essentially composed of three relationships. Superimposed on the moisture-density curve for each soil and each RC-3 increment are bar graphs representing confined and unconfined compressive strength values. The horizontal dotted line extending over the left portion of the figure represents the confined compressive strength of the soil with no admixture, compacted at maximum density and optimum moisture. The material was presented in this manner so as to afford an easy comparison of the effect of "dry-back" stage compaction.

The combination of Soil I and RC-3 compacted at a maximum stage failed to yield strength values as high as those for the soil with

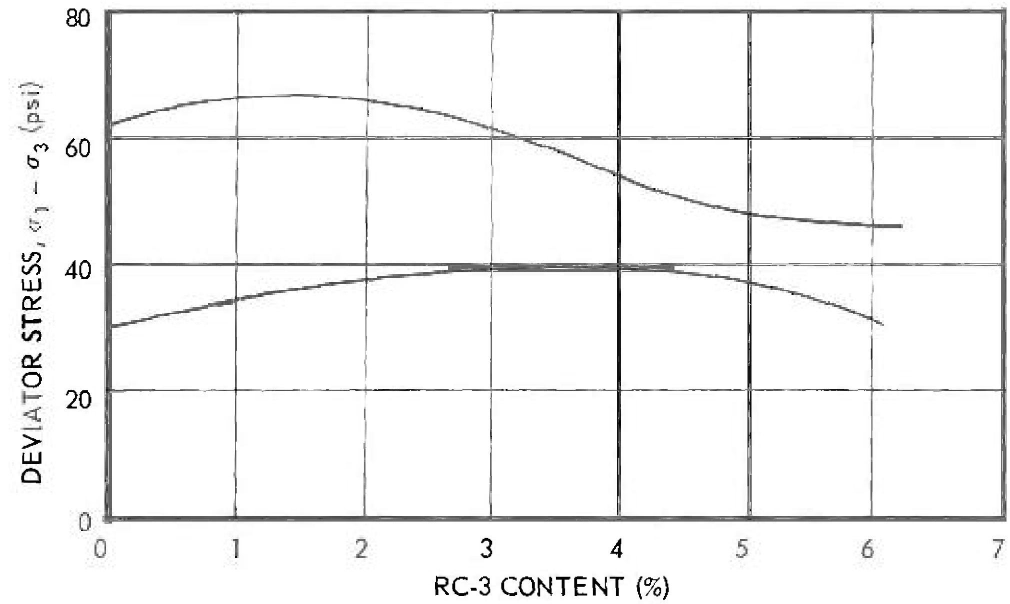

Figure 11. Variation in Deviator Stress with Increasing RC-3 Content, Soil I. Top Curve Q_3 = 20 psi, Bottom Curve Q_3 = 0.

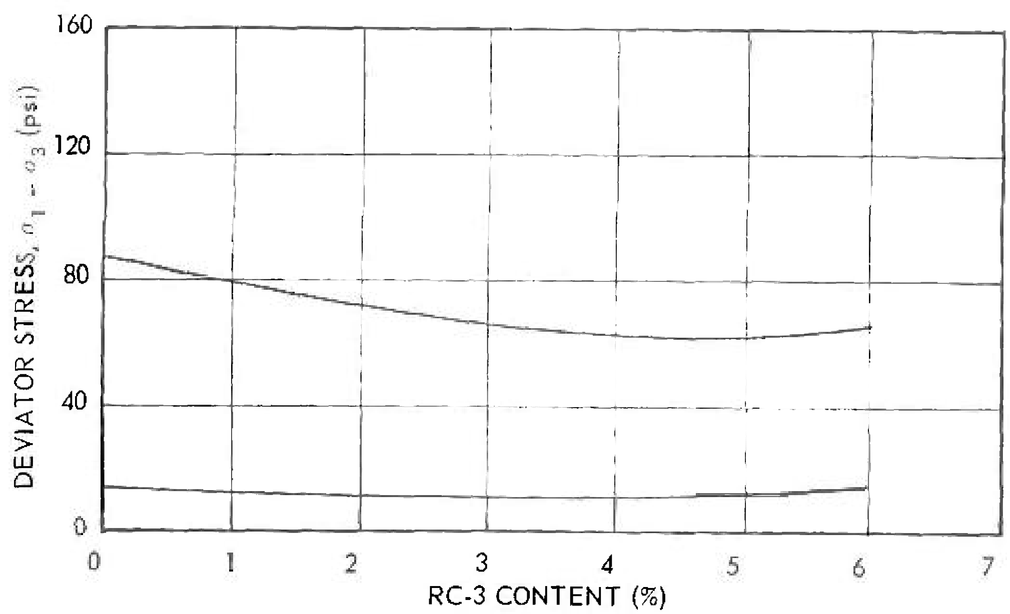

Figure 12. Variation in Deviator Stress with Increasing RC-3 Content, Soil II. Top Curve Q_3 = 20 psi, Bottom Curve Q_3 = 0.

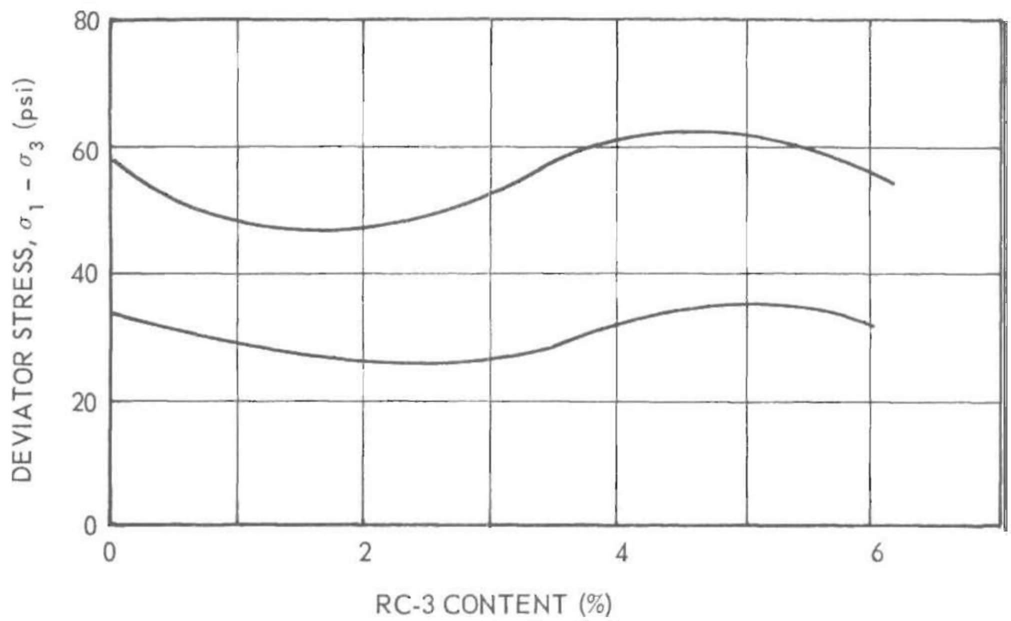

Figure 13. Variation in Deviator Stress with Increasing RC-3 Content, Soil IV. Top Curve Q_3 = 20 psi, Bottom Curve Q_3 = 0.

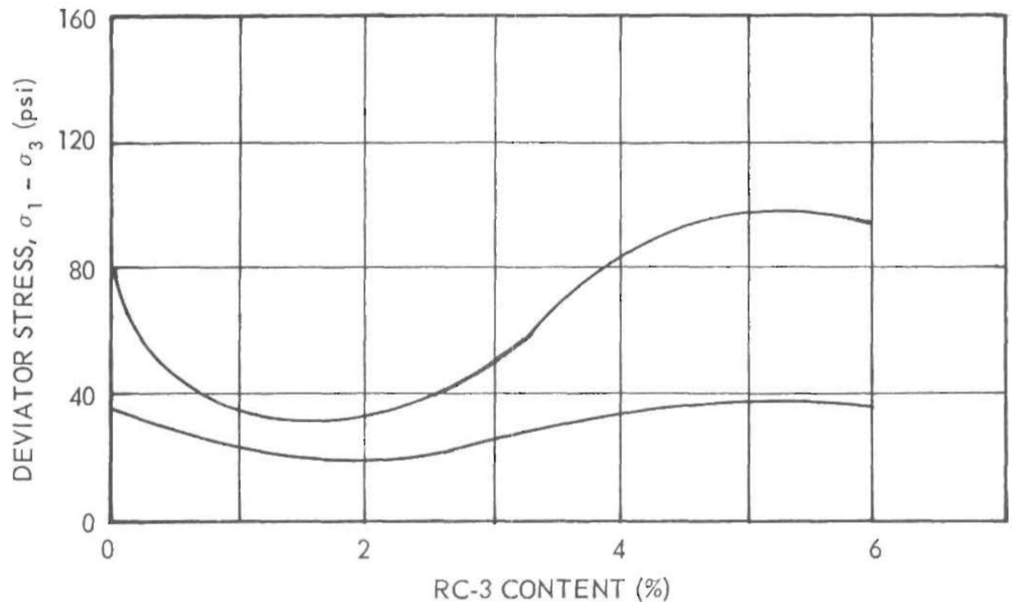

Figure 14. Variation in Deviator Stress with Increasing RC-3 Content, Soil VI. Top Curve Q_3 = 20 psi, Bottom Curve Q_3 = 0.

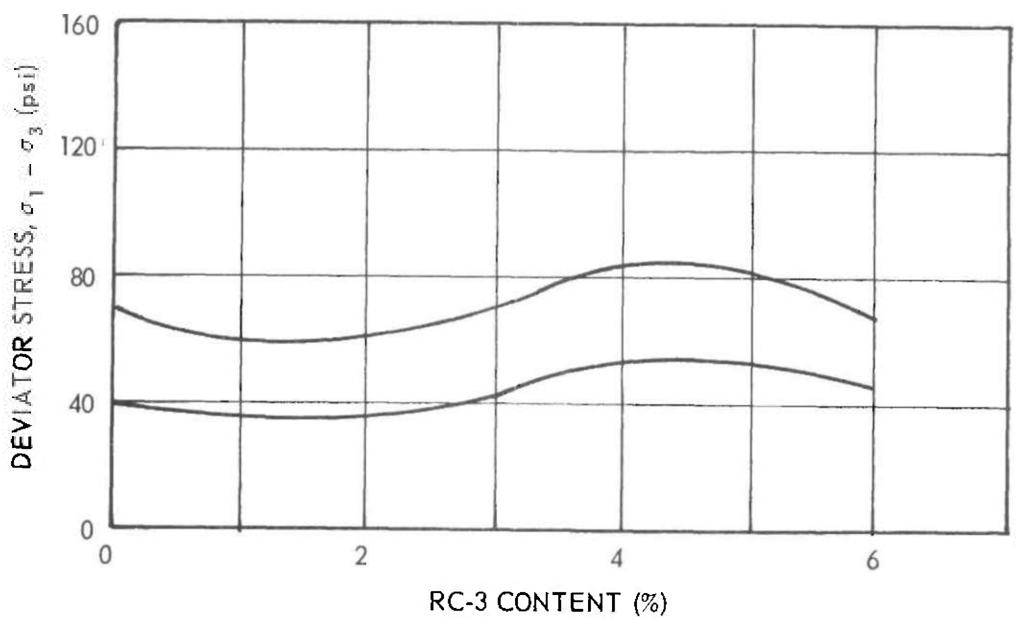

Figure 15. Variation in Deviator Stress with Increasing RC-3 Content, Soil VII. Top Curve Q_3 = 20 psi, Bottom Curve Q_3 = 0.

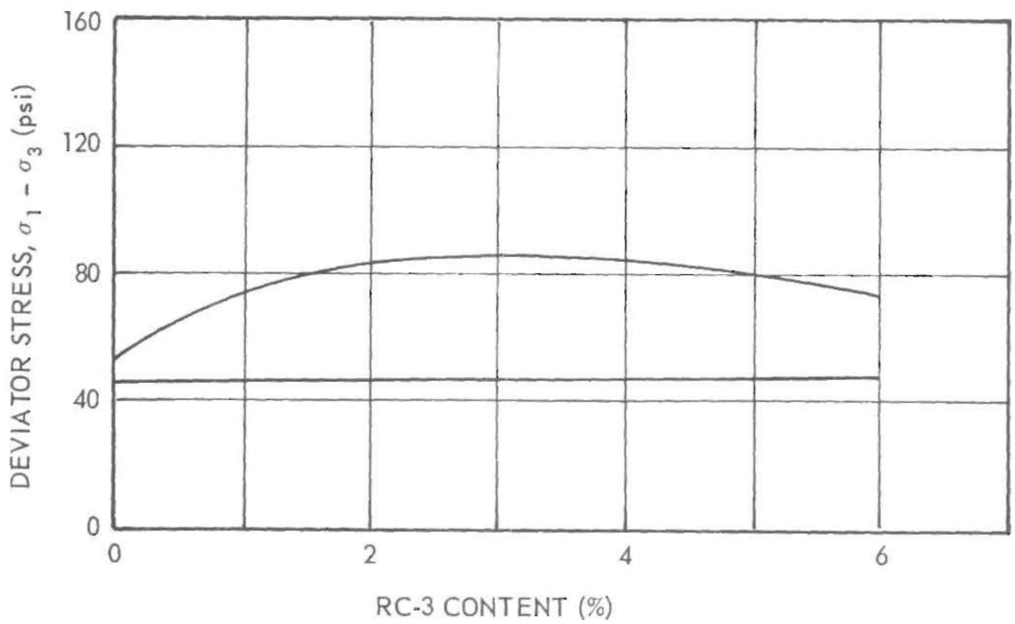

Figure 16. Variation in Deviator Stress with Increasing RC-3 Content, Soil VIII. Top Curve Q_3 = 20 psi, Bottom Curve Q_3 = 0.

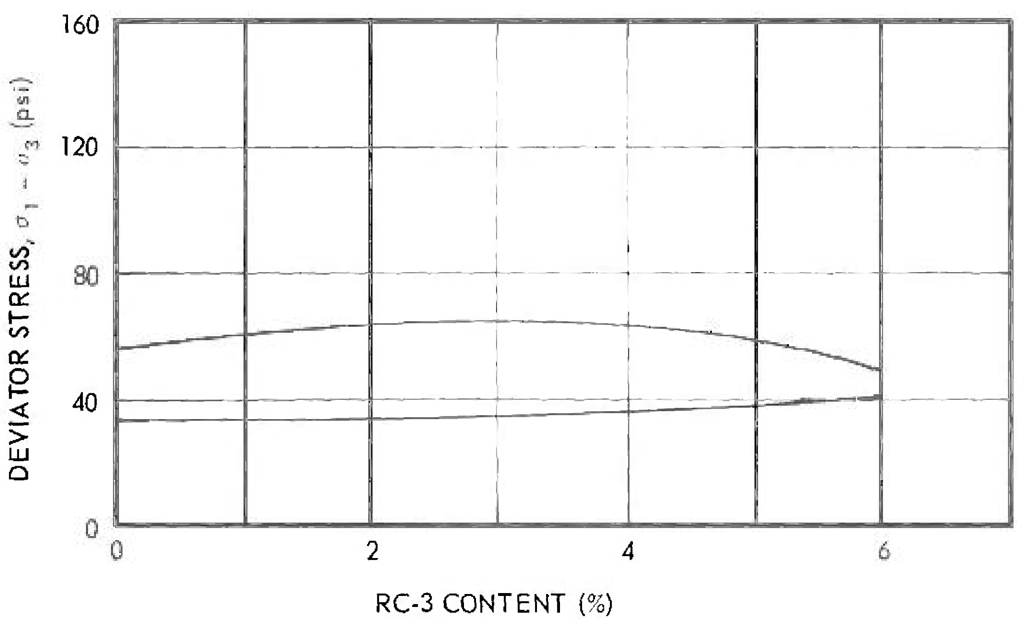

Figure 17. Variation in Deviator Stress with Increasing RC-3 Content, Soil IX. Top Curve Q_3 = 20 psi, Bottom Curve Q_3 = 0.

Table 3. Confined and Unconfined Compressive Strength Values (psi) for Maximum Stage Samples

RC-3(%)	0		2		4		6	
Soil	0*	20	0	20	0	20	0	20
I	32.0	62.0	38.0	64.5	39.4	54.1	30.0	46.0
II	15.0	85.2	10.0	72.0	13.0	61.0	14.0	64.0
III	--	--	--	--	--	--	1.1	43.0
IV	33.0	58.0	26.3	47.0	32.4	61.4	31.0	55.0
VI	37.0	89.0	19.4	32.9	34.0	86.3	35.9	91.9
VII	42.0	68.0	33.8	60.2	52.4	83.6	44.0	65.7
VIII	47.0	56.2	49.1	84.5	48.0	83.2	47.0	73.2
IX	32.0	56.0	35.1	61.8	34.9	63.7	36.0	46.2

*NOTE: 0 and 20 indicate confining pressure (σ_3) in psi.

no admixture. However, Soil I plus 2 per cent RC-3 dried back to 6.8 per cent showed a strength increase of 90 per cent. A general trend can be observed in Soil I plus RC-3 that is evidenced in other soils also. The drier the material is at compaction, the higher the strength values are when compared to the maximum stage samples for the particular combination of materials. This was true in Soil I plus 2, 4 and 6 per cent RC-3. However, optimum results were obtained with 2 per cent RC-3.

A large quantity of Soils II, III and IV was expended in developing the laboratory design procedure. Hence, complete application of maximum and dry-back stage strength evaluations could not be made.

The addition of RC-3 to Soil II reduced the strength slightly. Only one dry-back stage was compacted (at 4% RC-3) and this stage failed to equal the strength of the soil with no admixture.

Problems in sample compaction were encountered with Soil III, a uniform beach sand. Maximum stage strength samples lacked sufficient strength to enable triaxial shear testing. Hence, there is no curve for Soil III, maximum stage samples. However, a total of four dry-back stages were completed, the results of which are shown in Figures 22 and 23. Maximum strength occurred at 2 per cent and 4 per cent RC-3 content when dried back to a liquid content of 5.3 per cent.

Strength samples compacted at maximum density and optimum moisture content for Soil IV plus RC-3 indicated an overall reduction in strength when compared to the strength values of Soil IV with no admixture. But, Soil IV plus 2 per cent RC-3 dried back to 10.9 per cent liquid content underwent a considerable strength gain as seen in Figure 24.

As mentioned previously, Soil V was not available for this investigation.

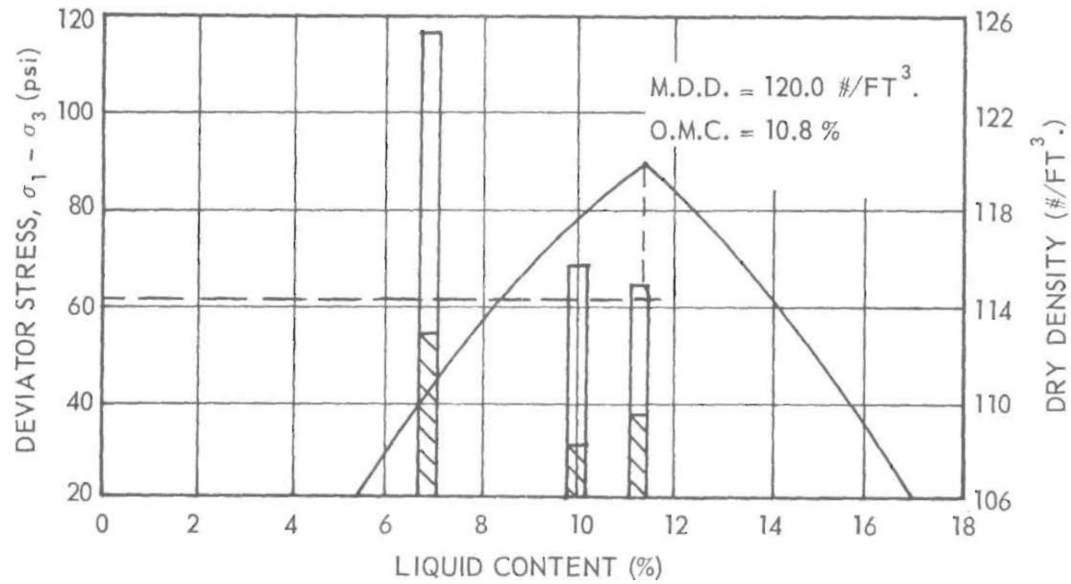

Figure 18. Comparison of Dry-Back Stages and Maximum Stage, Soil I + 2% RC-3.

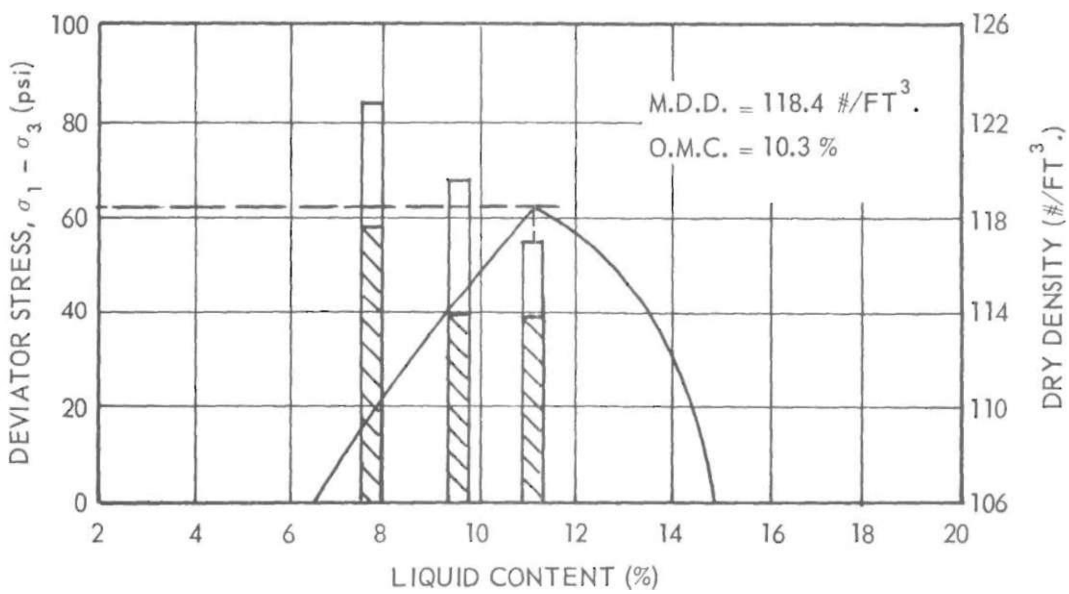

Figure 19. Comparison of Dry-Back Stages and Maximum Stage, Soil I + 4 % RC-3.

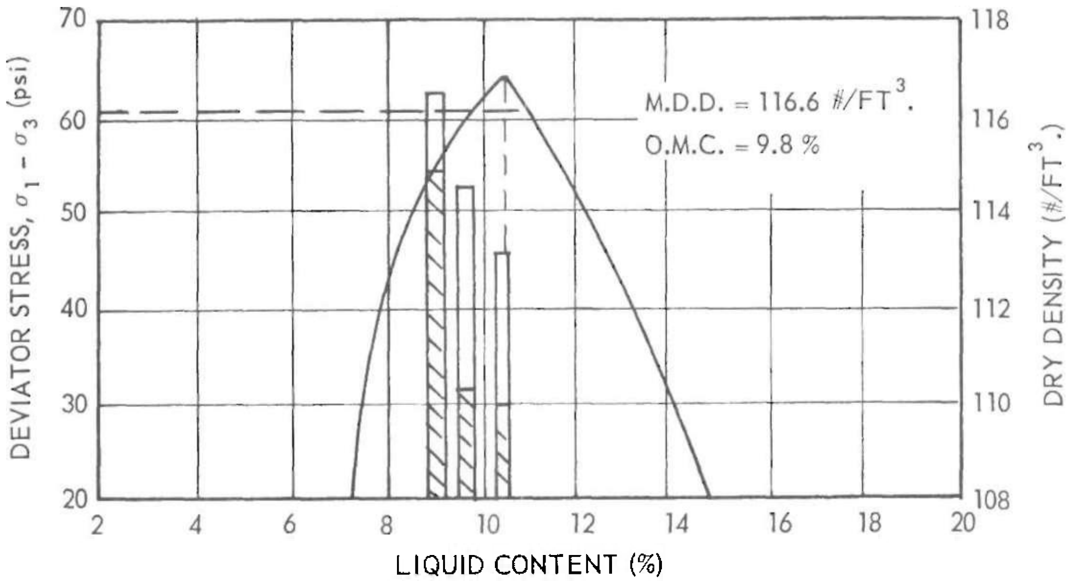

Figure 20. Comparison of Dry-Back Stages and Maximum Stage, Soil I + 6% RC-3.

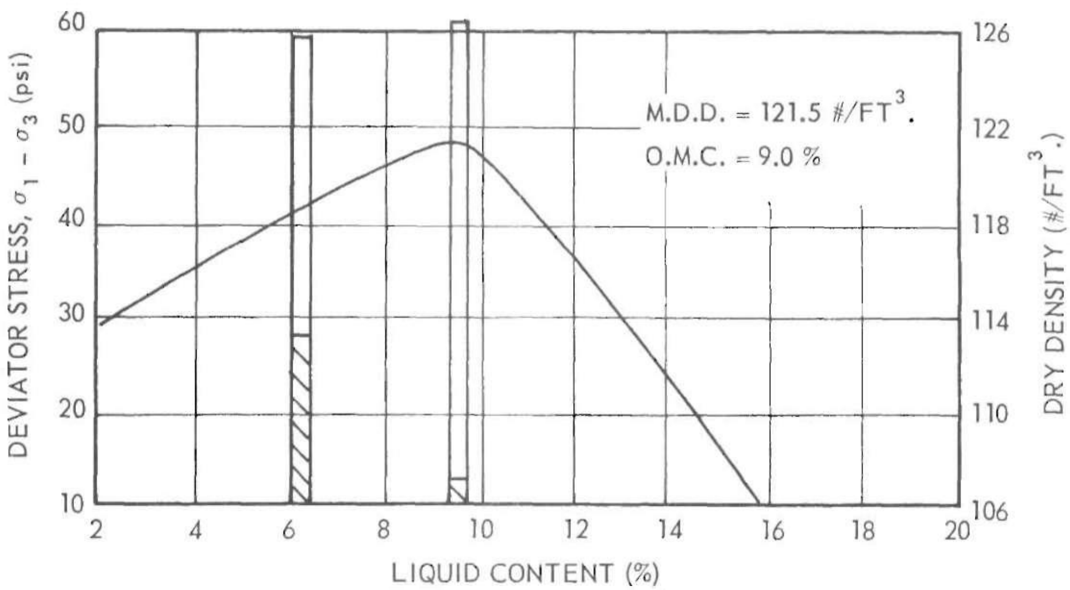

Figure 21. Comparison of Dry-Back Stages and Maximum Stage, Soil II + 4% RC-3.

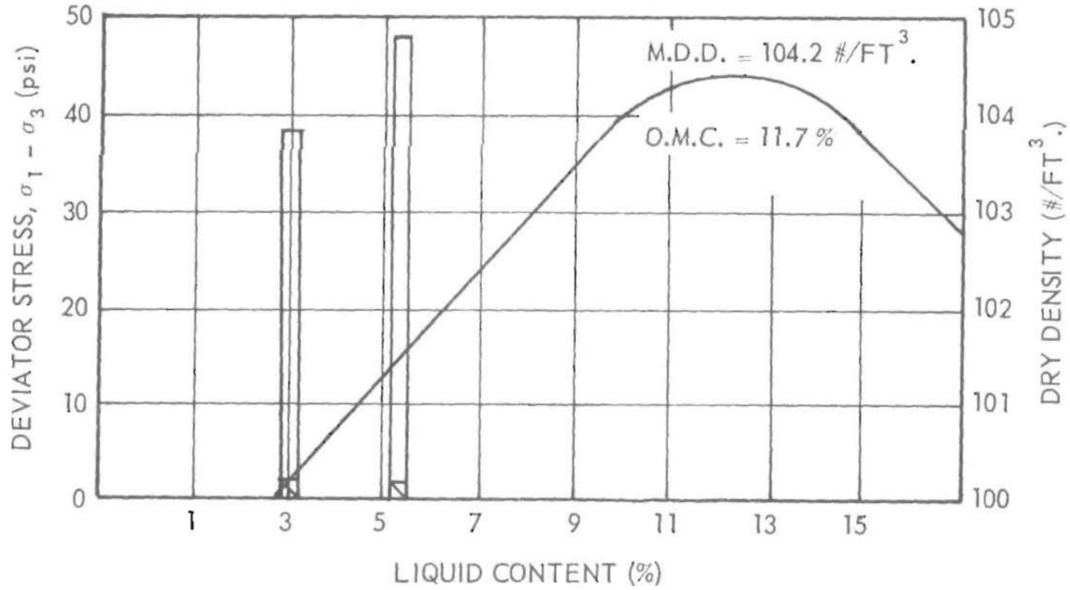

Figure 22. Comparison of Dry-Back Stages and Maximum Stage, Soil III + 2% RC-3.

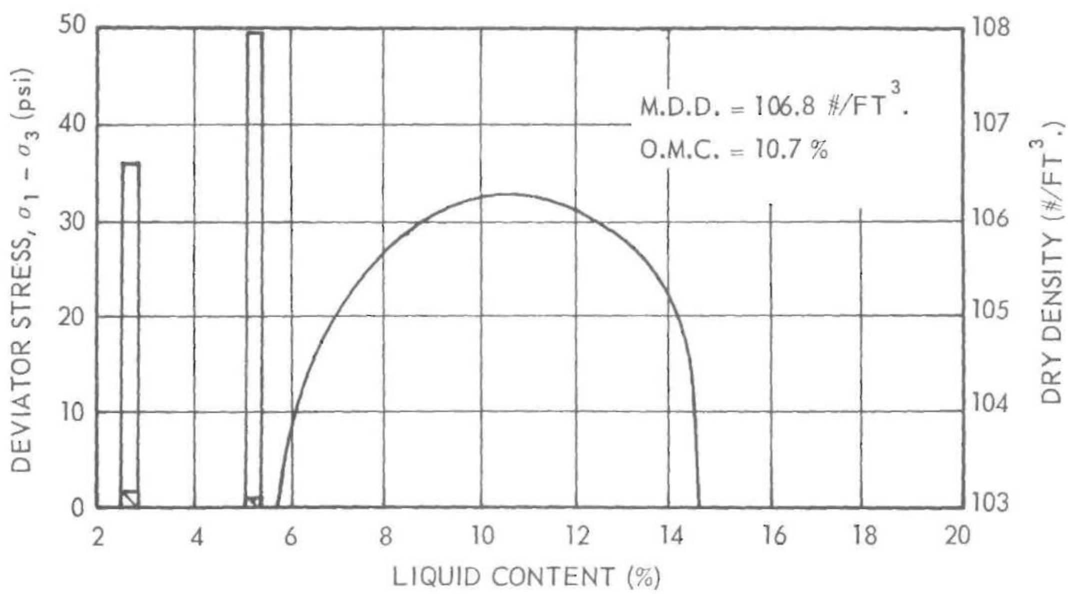

Figure 23. Comparison of Dry-Back Stages and M ximum Stage, Soil III + 4% RC-3.

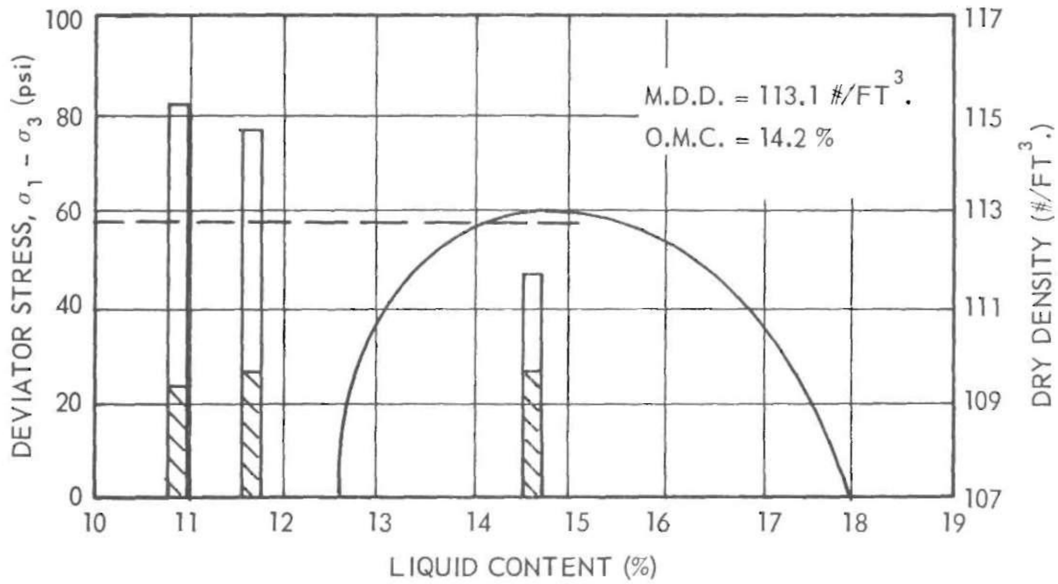

Figure 24. Comparison of Dry-Back Stages and Maximum Stage, Soil IV + 2% RC-3.

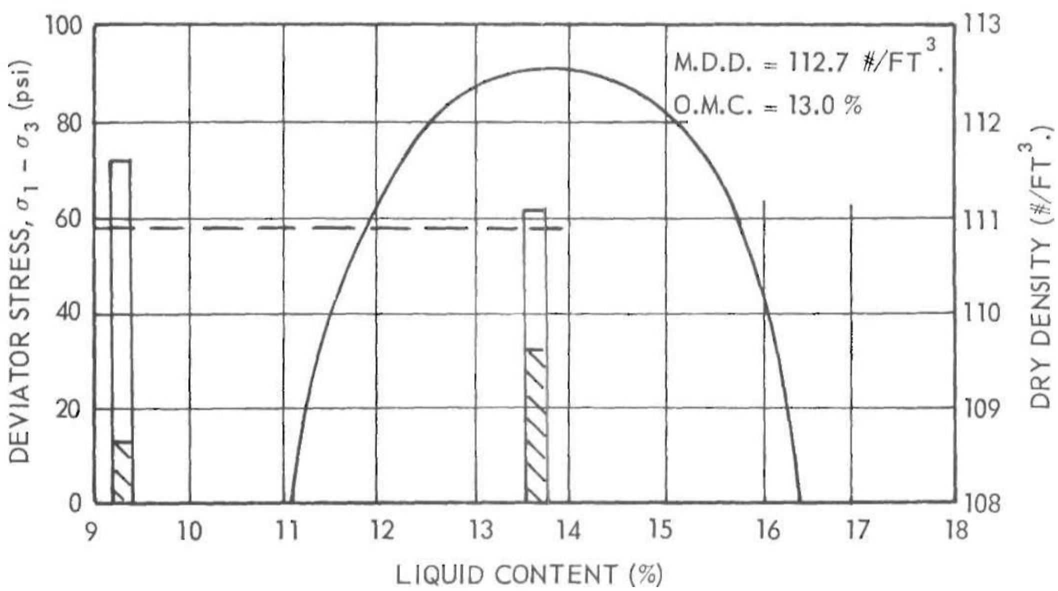

Figure 25. Comparison of Dry-Back Stages and Maximum Stage, Soil IV + 4% RC-3.

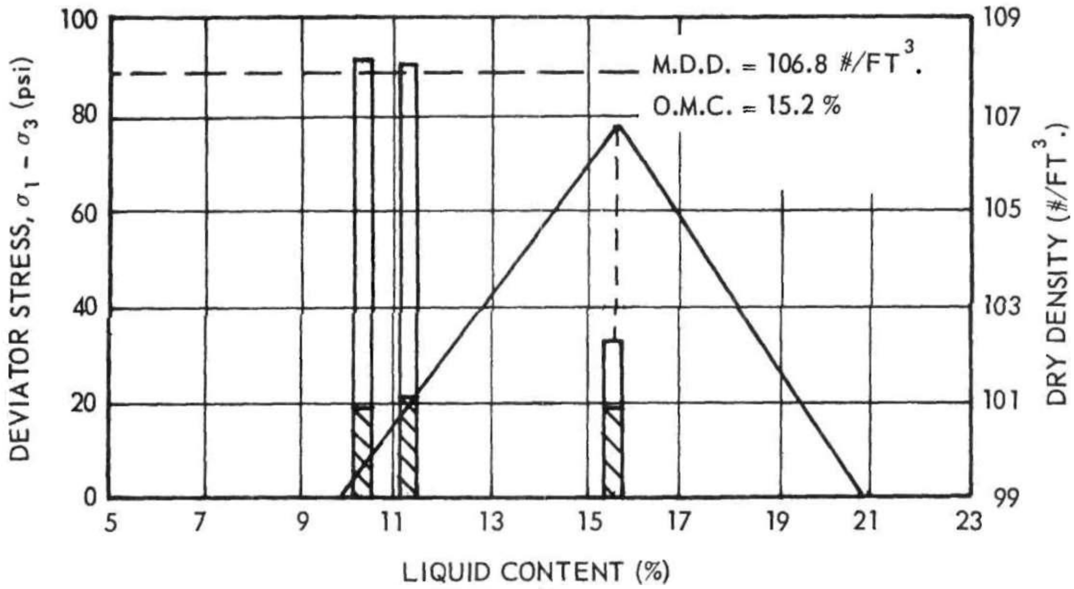

Figure 26. Comparison of Dry-Back Stages and Maximum Stage, Soil VI + 2% RC-3.

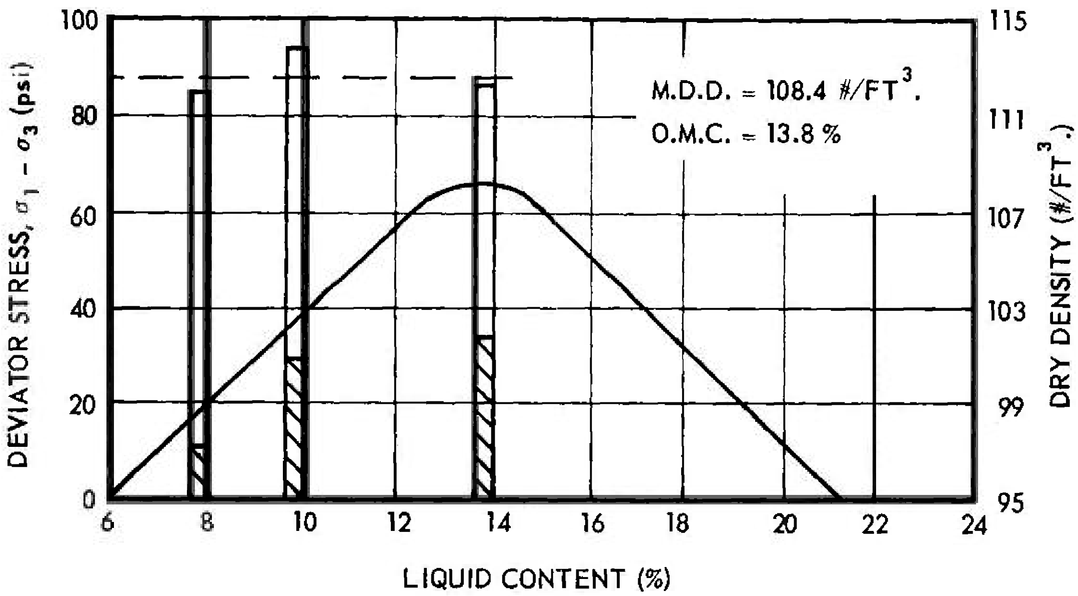

Figure 27. Comparison of Dry-Back Stages and Maximum Stage, Soil VI + 4% RC-3.

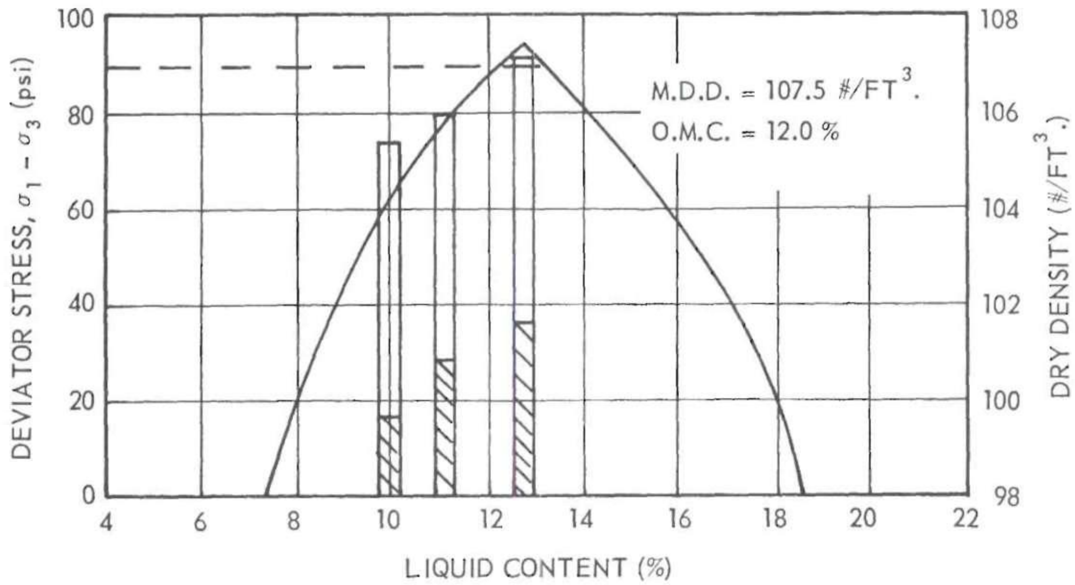

Figure 28. Comparison of Dry-Back Stages and Maximum Stage, Soil VI + 6% RC-3.

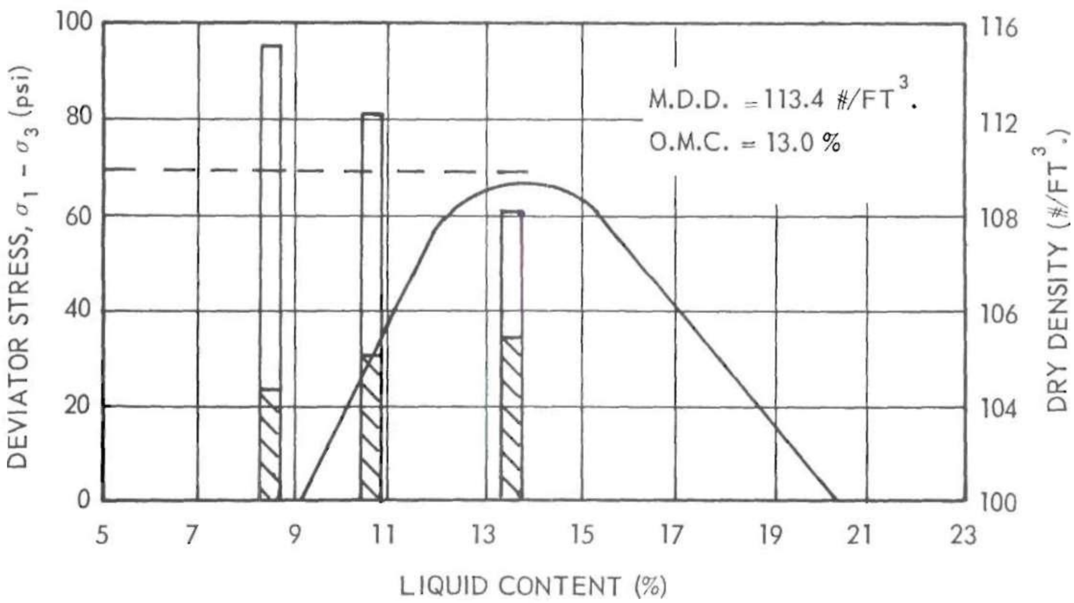

Figure 29. Comparison of Dry-Back Stages and Maximum Stage, Soil VII + 2% RC-3.

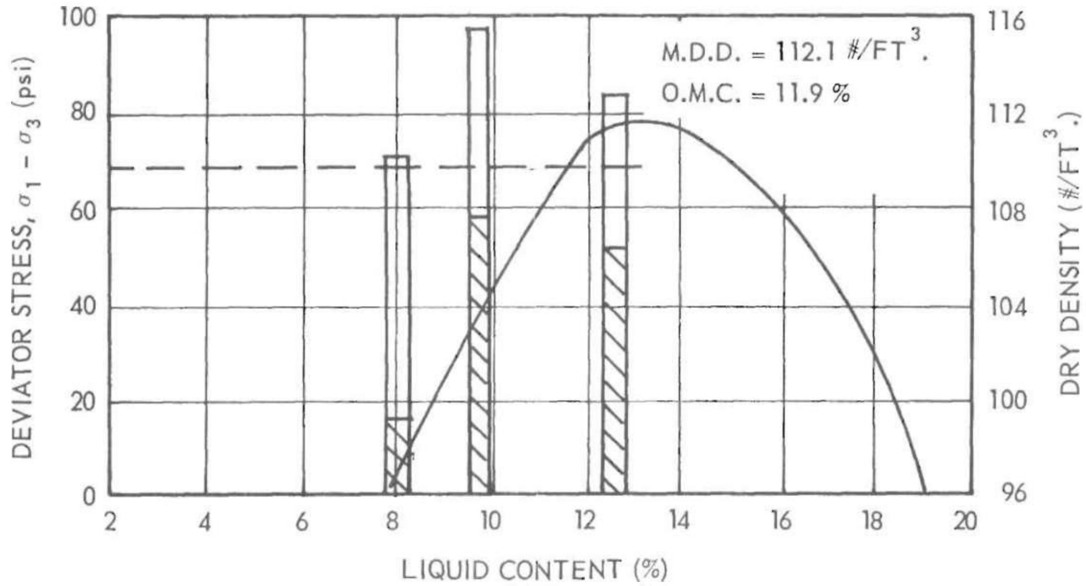

Figure 30. Comparison of Dry-Back Stages and Maximum Stage, Soil VII + 4% RC-3 .

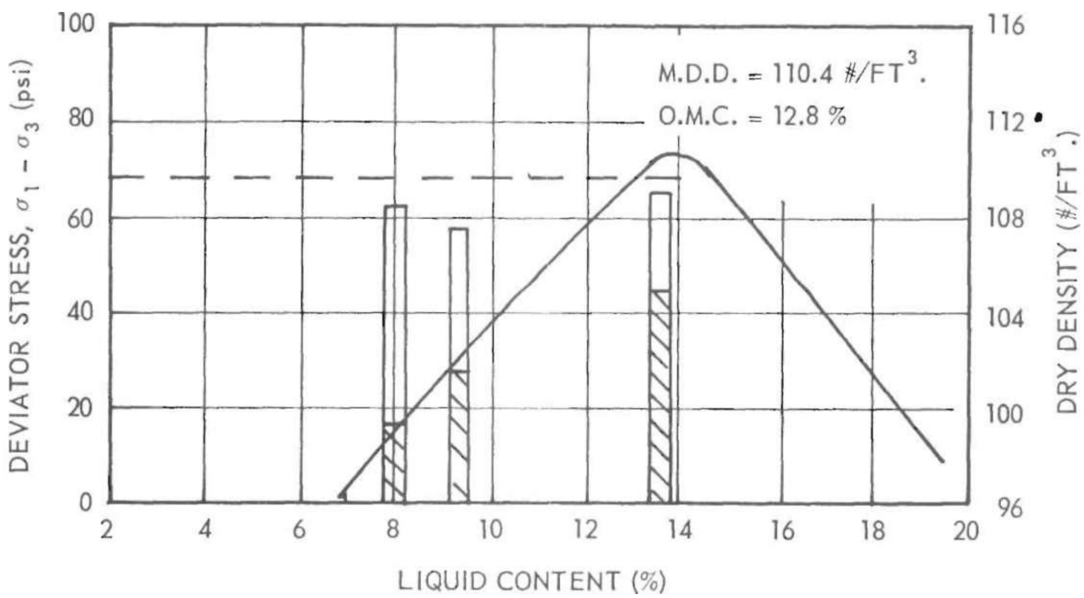

Figure 31. Comparison of Dry-Back Stages and Maximum Stage, Soil VII + 6% RC-3.

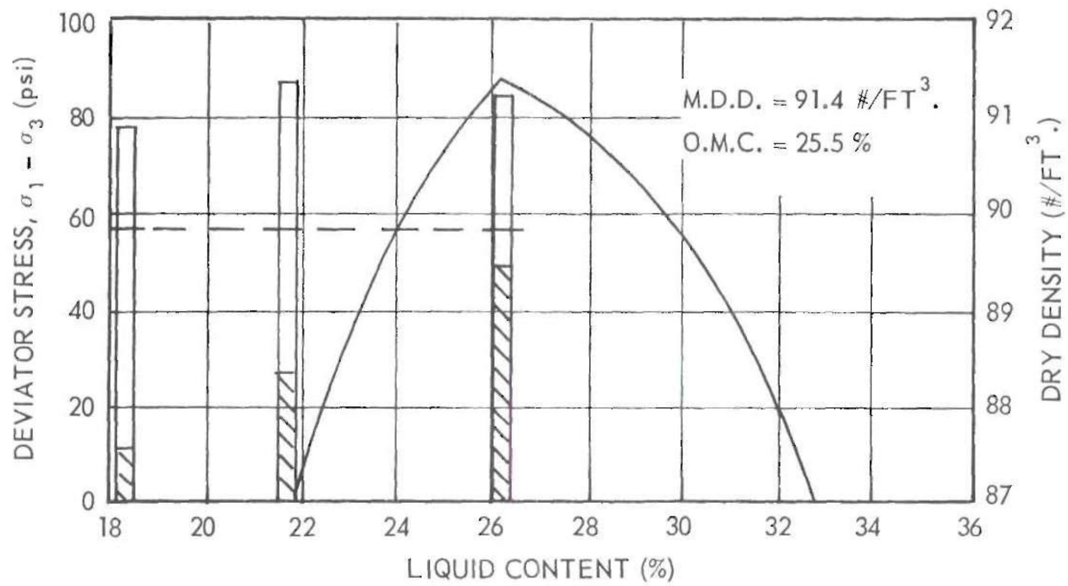

Figure 32. Comparison of Dry-Back Stages and Maximum Stage, Soil VIII + 2% RC-3.

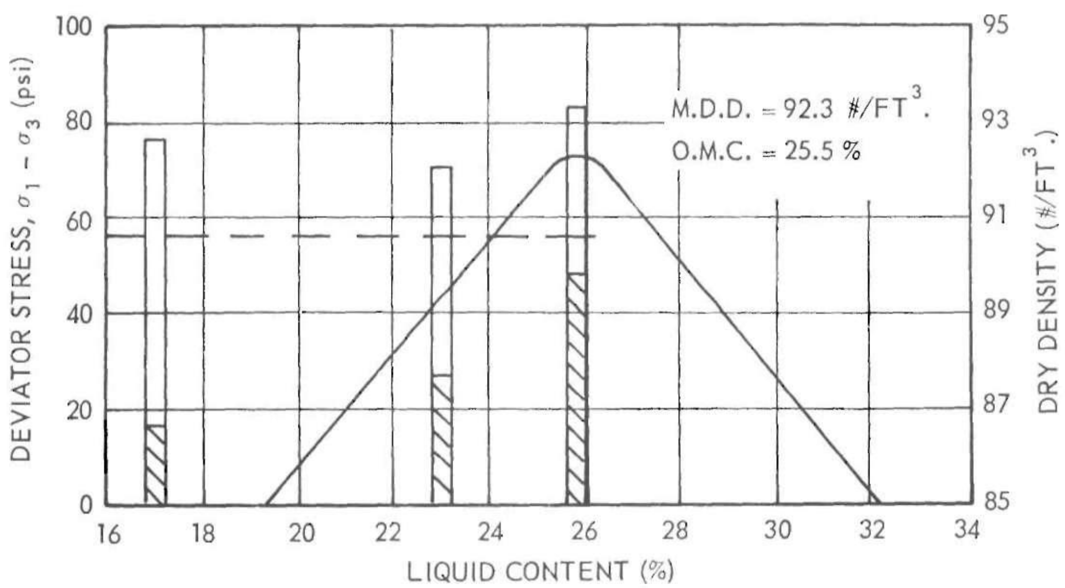

Figure 33. Comparison of Dry-Back Stages and Maximum Stage, Soil VIII + 4% RC-3.

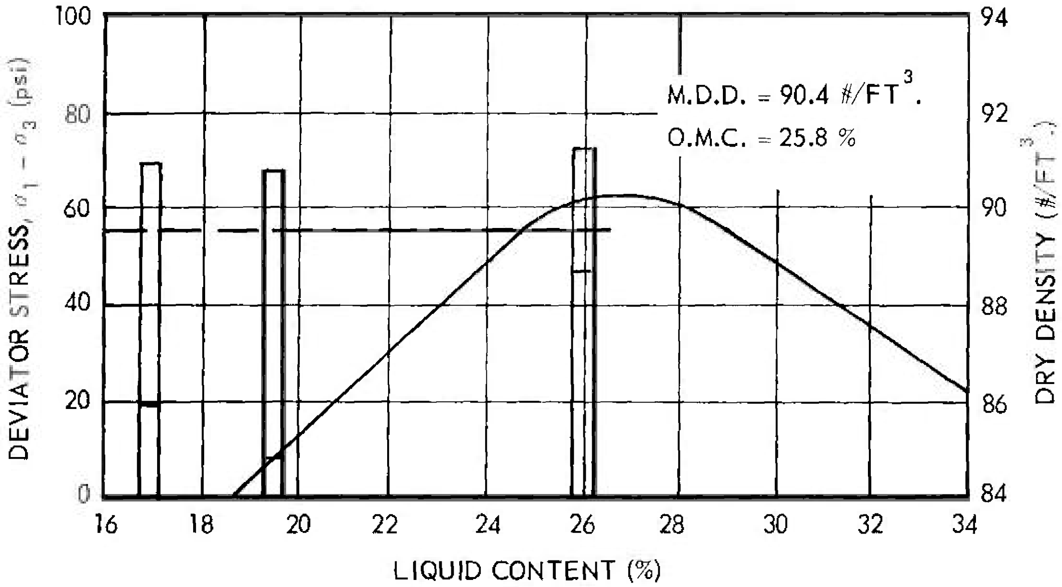

Figure 34. Comparison of Dry-Back Stages and Maximum Stage, Soil VIII + 6% RC-3.

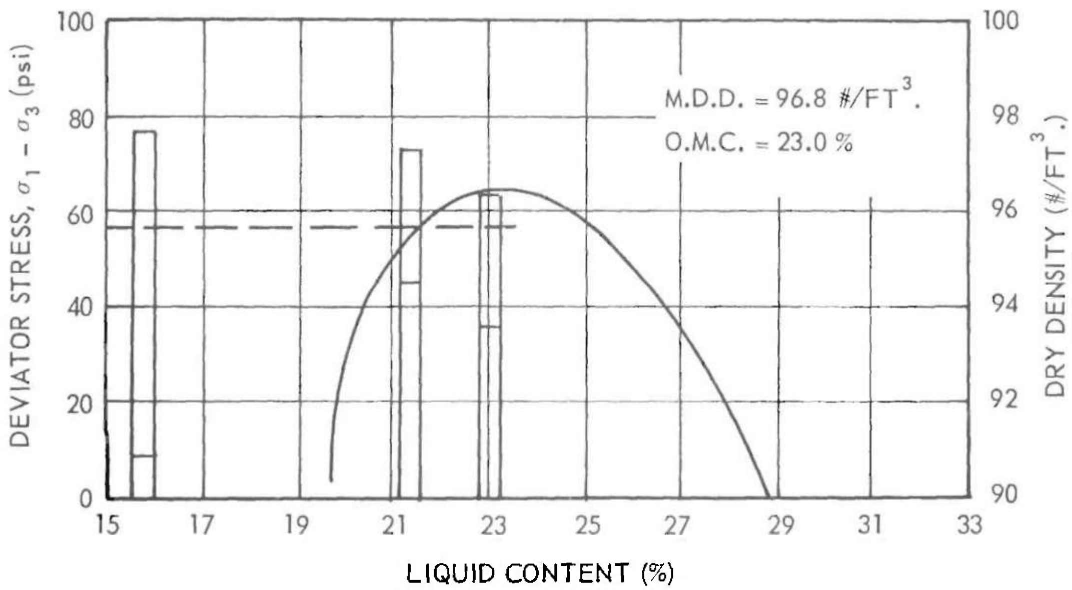

Figure 35. Comparison of Dry-Back Stages and Maximum Stage, Soil IX + 2% RC-3.

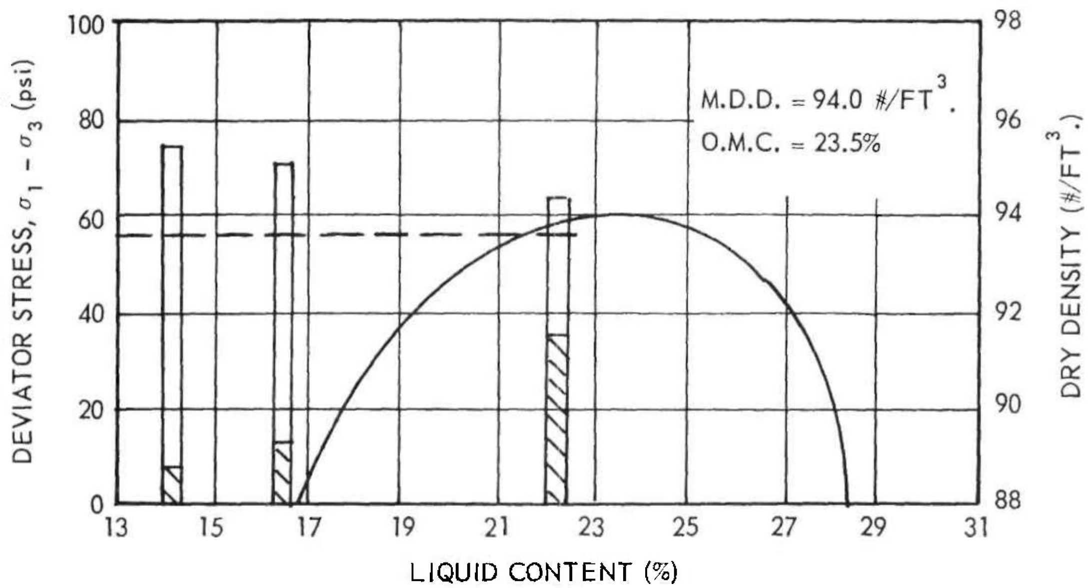

Figure 36. Comparison of Dry-Back Stages and Maximum Stage, Soil IX + 4% RC-3.

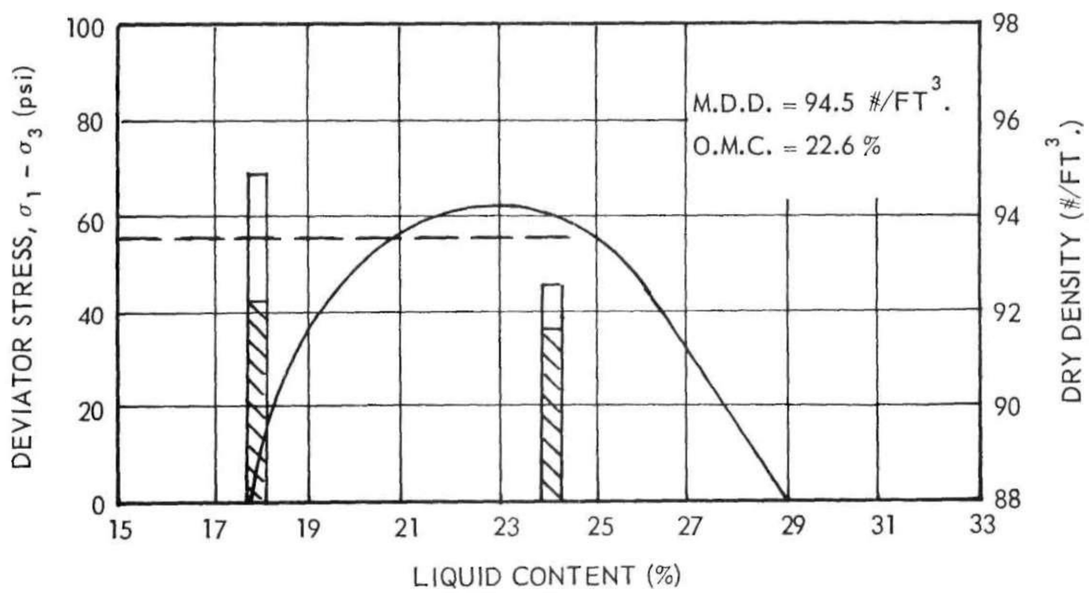

Figure 37. Comparison of Dry-Back Stages and Maximum Stage, Soil IX + 6% RC-3.

Soil VI experienced a marked reduction in strength when combined with 2 per cent RC-3 and compacted in a maximum stage. However, this reduction in strength was regained at 4 and 6 per cent RC-3. Dry-back stages had a negligible effect on strength values.

A strength gain was evidenced for Soil VII combined with 4 per cent RC-3 and compacted at maximum density and optimum moisture. Dry-back stages had a negligible effect on strength values.

A strength gain was evidenced for Soil VII combined with 4 per cent RC-3 and compacted at maximum density and optimum moisture. Dry-back stage compaction was successful in that significant increases in strength were realized. An inspection of Figure 29 and Figure 30 indicates that optimum results were obtained at 2 per cent RC-3 compacted at a liquid content of 8.4 per cent and at 4 per cent RC-3 dried back to 9.7 per cent. In a situation such as this the optimum cutback asphalt content is obviously 2 per cent.

The state of Georgia has an abundant supply of plastic, red clays that possess adequate strength properties if moisture content is controlled to within reasonable limits. Soil VIII is representative of this group. Combining cutback asphalt with Soil VIII increased strength values as much as 65 per cent (See Figure 32). In every stage, whether maximum or dry-back the compressive strength of Soil VIII was enhanced by the addition of cutback asphalt. The optimum RC-3 content for Soil VIII was 2 per cent.

Soil IX, a moderately plastic, silty clay, reacted in much the same manner as Soil VIII when combined with RC-3. Slight increases in strength were realized at maximum stage compaction while further increases were noticeable in dry-back stages. Once again, optimum RC-3 content was 2 per cent.

Cohesion (c) and angle of internal friction Ø.--Graphical representation of the equations for shear and normal stress on a plane inclined at some angle with the horizontal result in a series of semi-circles of increasing radius. This representation, known as Mohr's diagram, yields readily available values of two important strength parameters in soil construction. The cohesion (c) of a soil is the y-axis intercept of a line drawn mutually tangent to each semi-circle. The inclination of this tangent with the horizontal is the angle of internal friction, Ø.

To successfully describe these two strength parameters, at least three lateral pressures usually should be used. In this research it was found necessary to limit these lateral pressures to 0 and 20 psi.

Mohr's diagrams for each soil and test increment of RC-3 for both the maximum and dry-back stages are included in the appendix as Figures 38 through 101.

CHAPTER V

CONCLUSIONS

An investigation of the characteristics of soil-water-RC-3 mixtures has made evident the following conclusions:

1. The moisture content that affords best distribution of soil and RC-3 occurs near OMC for most soils.
2. The addition of RC-3 to well-graded soils causes a reduction in density while an increase in density occurs when RC-3 is combined with a uniformly graded soil.
3. The effect of RC-3 on the moisture requirements of a soil is varied but in most cases less moisture is required at maximum density when the soil is compacted in combination with RC-3.
4. The compressive strength of soil-water-RC-3 mixtures decreases with a decrease in density and increases with a decrease in moisture content.
5. Maximum strength characteristics are not coincident with maximum density characteristics.
6. Strength parameters of the soils tested are not materially increased by the addition of RC-3.
7. Maximum benefit from the combination of soil and RC-3 can be achieved by:
    a. Mixing at or near OMC of the soil proper.
    b. Allowing the mixture to aerate prior to compaction.
    c. Compaction at the dry-back stage that coincides with maximum strength.
8. The optimum asphalt content varies with soil type but is generally found in the range of 2 to 4 per cent.

CHAPTER VI

RECOMMENDATIONS

The following recommendations apply to the design and control of soil-bituminous bases and subgrades:

1. Each soil has a moisture content, usually near OMC, that facilitates distribution of cutback asphalt. This moisture content can be determined by visual observation and should be provided when mixing soil and RC-3.
2. The moisture content at which soil and RC-3 are mixed does not necessarily coincide with the moisture content corresponding to maximum strength characteristics. Therefore in most cases the mixture must be aerated until the proper "stage" is reached.
3. Field construction can be controlled by frequent density determinations during the aeration process.
4. After mixing and compaction, allow as much free moisture as possible to evaporate since subsequent strength gains will result from an initial decrease in water content.

The following recommendations are made pertaining to the need for further research of this nature:

1. A definite need exists for the determination of stress distribution beneath paving components and for the application of such information to lateral pressures and end restraints imposed on laboratory specimens.

2. Further study is necessary to evaluate soil-bituminous mixtures from the standpoint of watertightness and durability rather than on the basis of compressive strength alone.

3. The advantages of different grades of cutback asphalt as well as the use of emulsions must be investigated if maximum benefit is to be achieved from bituminous stabilization.

APPENDIX

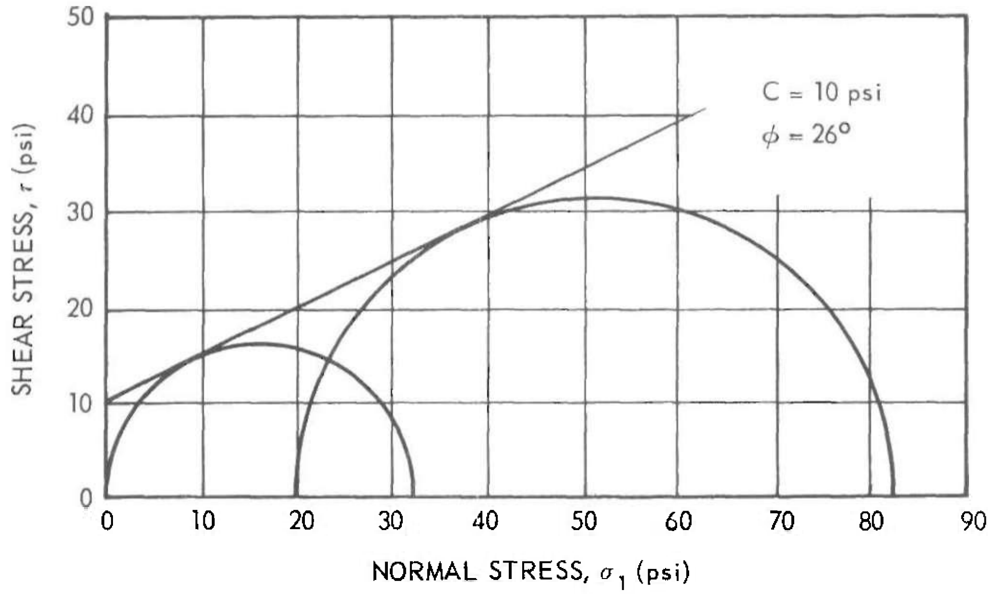

Figure 38. Mohr Diagram, Soil I.

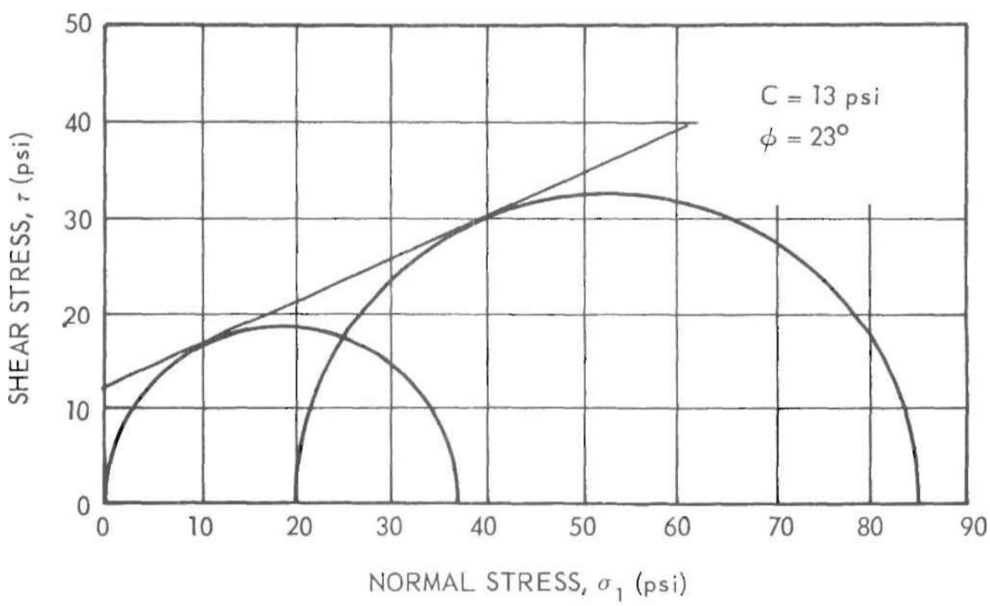

Figure 39. Mohr Diagram, Soil I + 2% RC-3, Stage Maximum.

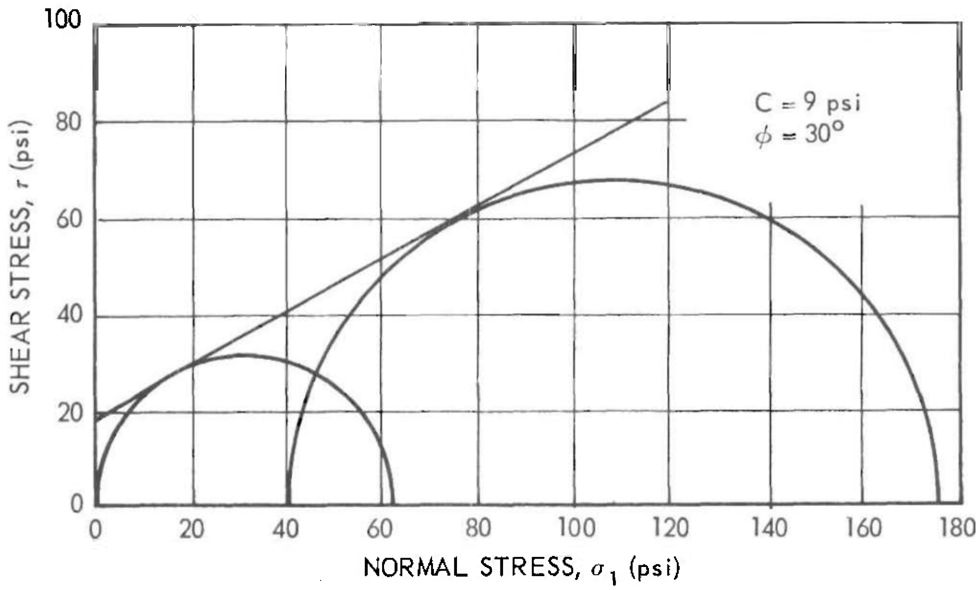

Figure 40. Mohr Diagram, Soil I + 2% RC-3, Stage 10.0.

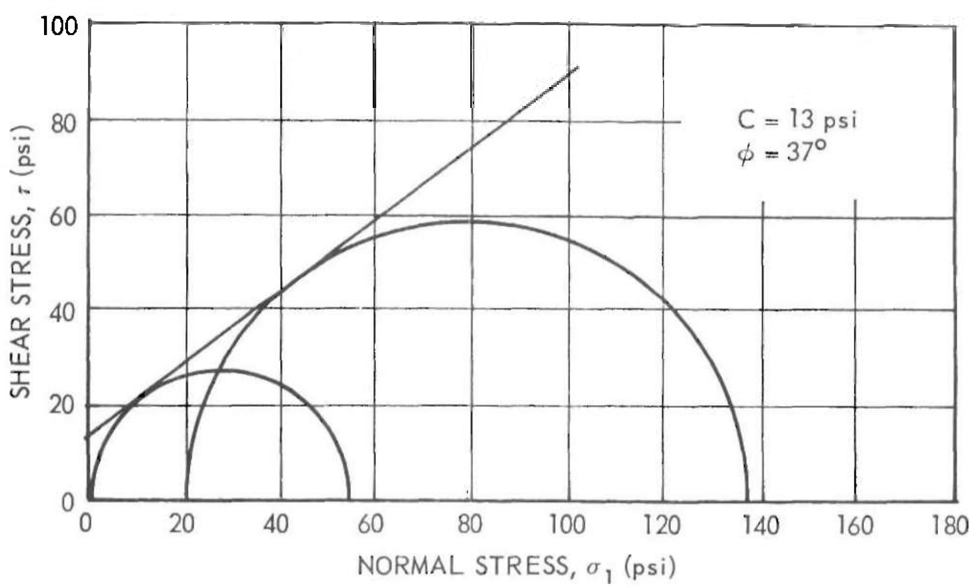

Figure 41. Mohr Diagram, Soil I + 2% RC-3, Stage 6.8.

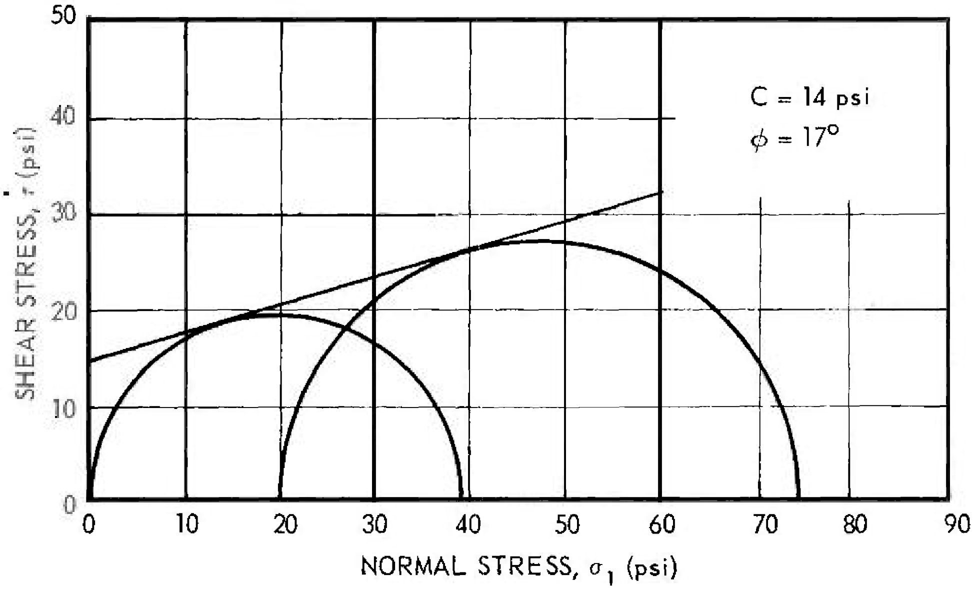

Figure 42. Mohr Diagram, Soil I + 4% RC-3, Stage Maximum.

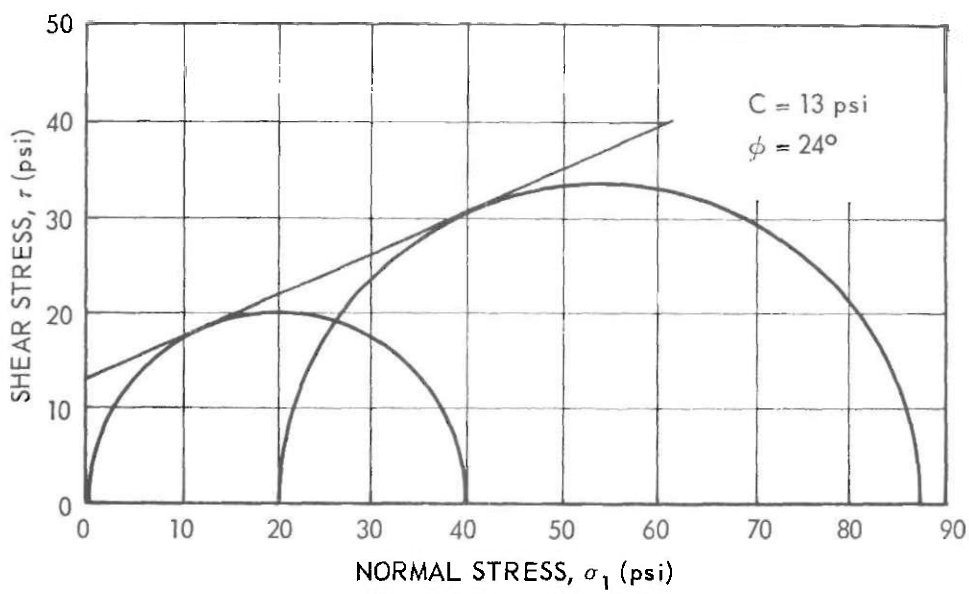

Figure 43. Mohr Diagram, Soil I + 4% RC-3, Stage 9.5.

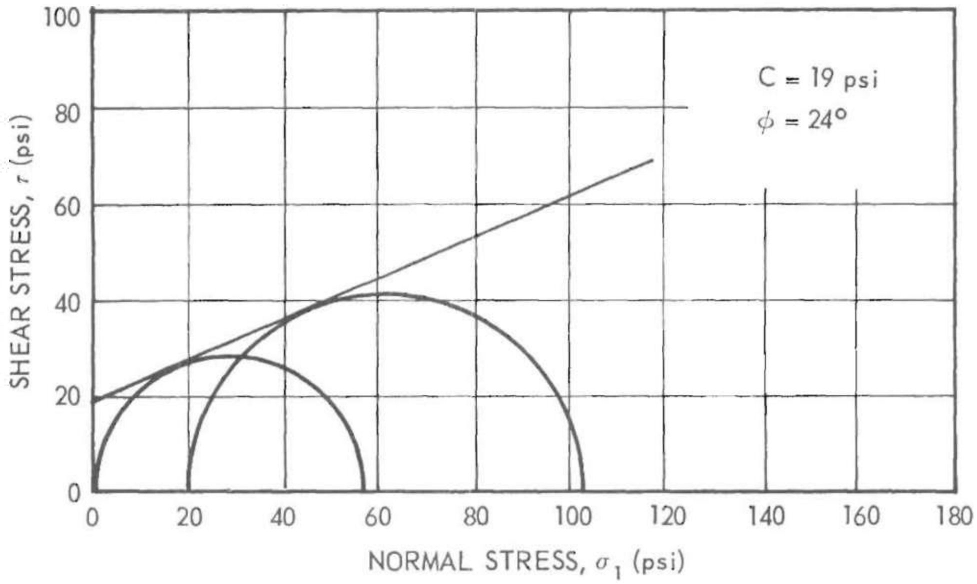

Figure 44. Mohr Diagram, Soil I + 4% RC-3, Stage 7.8.

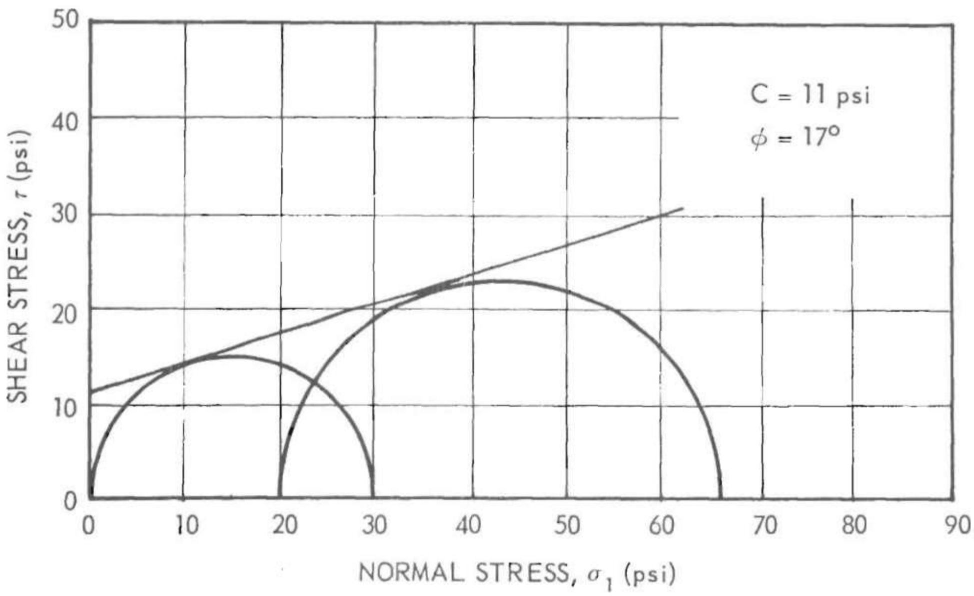

Figure 45. Mohr Diagram, Soil I + 6% RC-3, Stage Maximum.

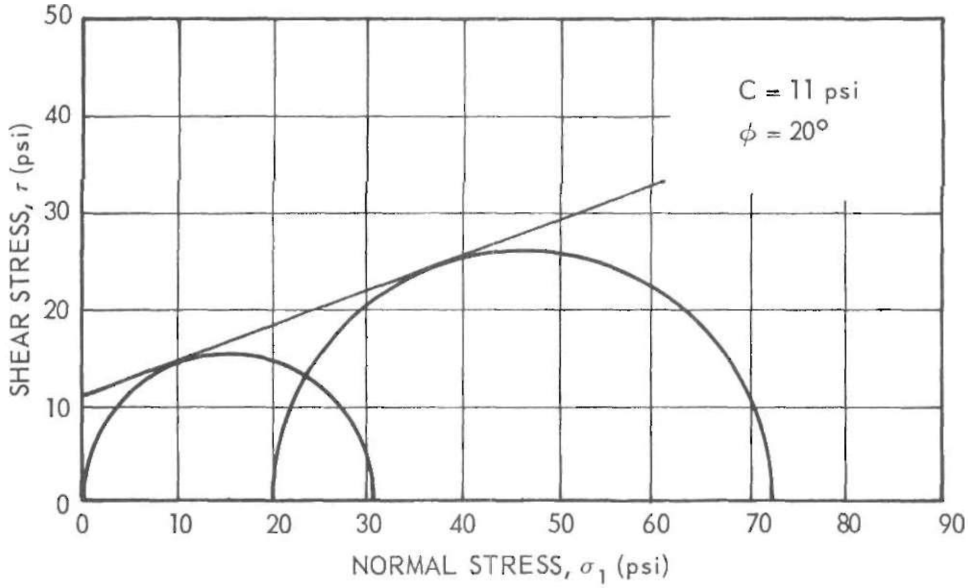

Figure 46. Mohr Diagram, Soil I + 6% RC-3, Stage 9.7.

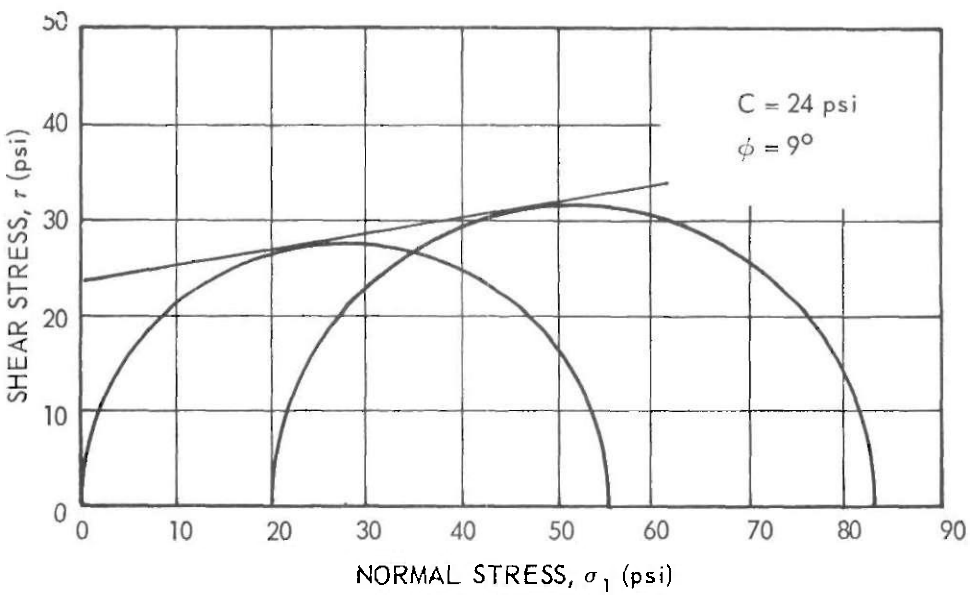

Figure 47. Mohr Diagram, Soil I + 6% RC-3, Stage 9.3.

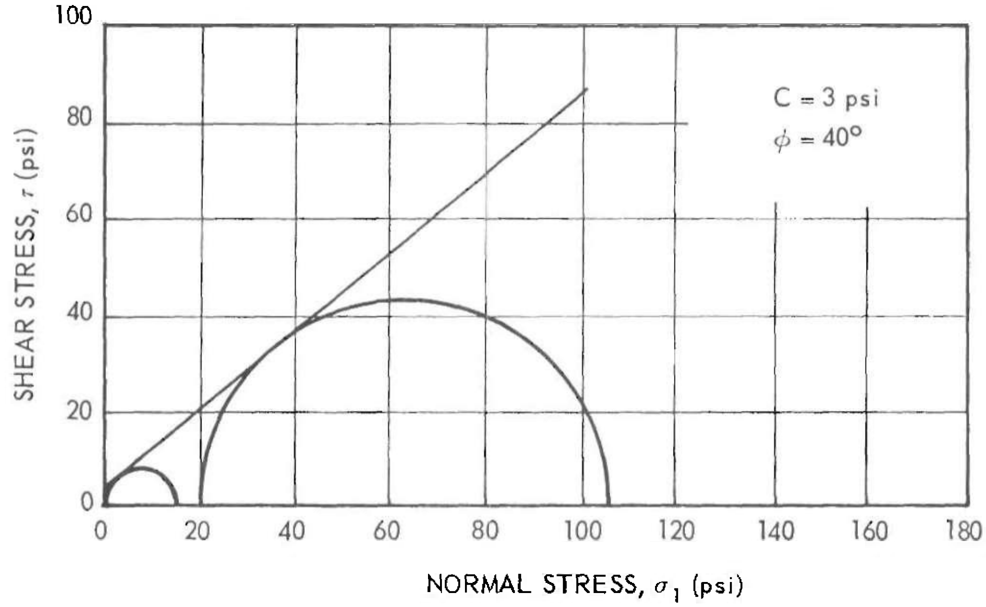

Figure 48. Mohr Diagram, Soil II.

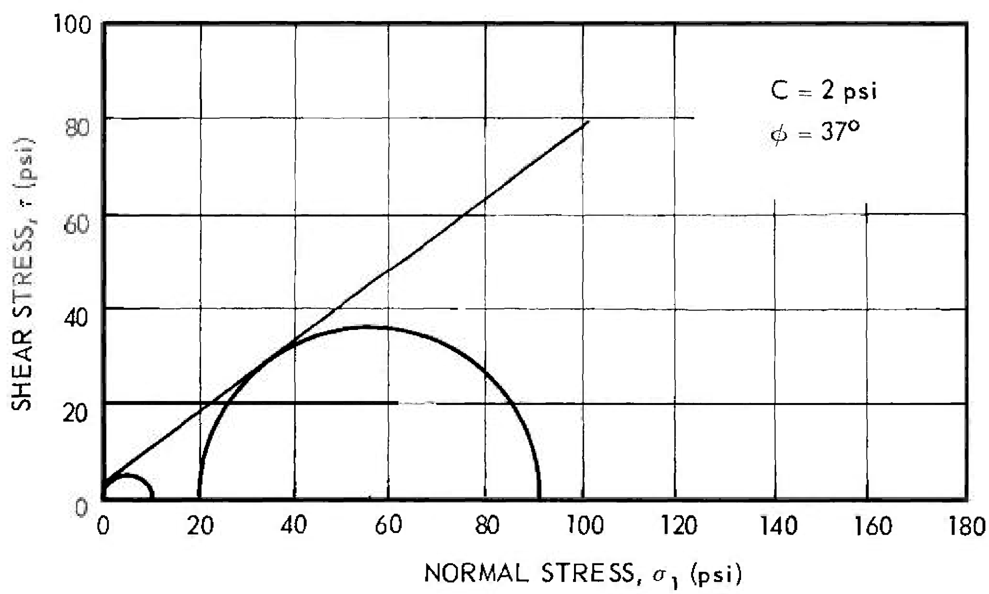

Figure 49. Mohr Diagram, Soil II + 2% RC-3, Stage Maximum.

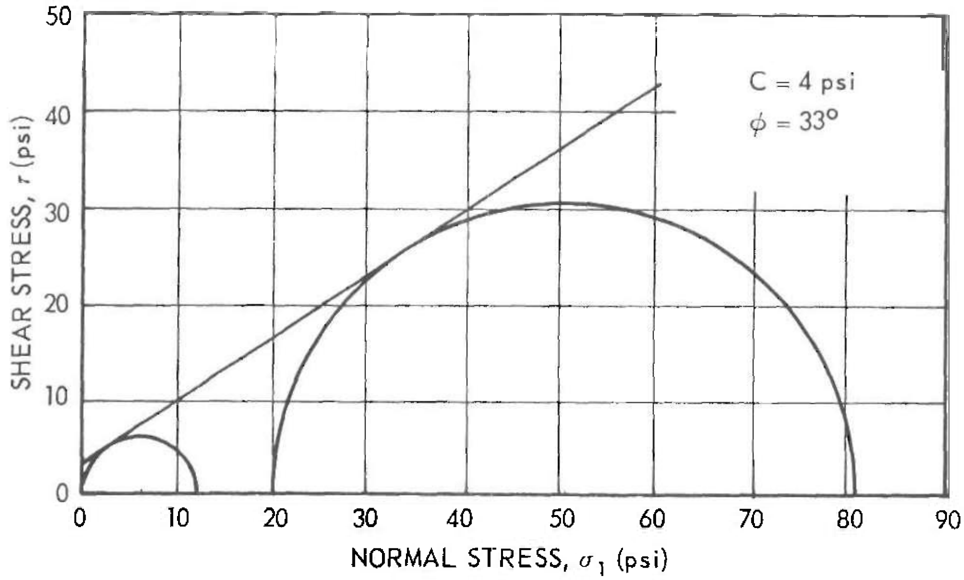

Figure 50. Mohr Diagram, Soil II + 4% RC-3, Stage Maximum.

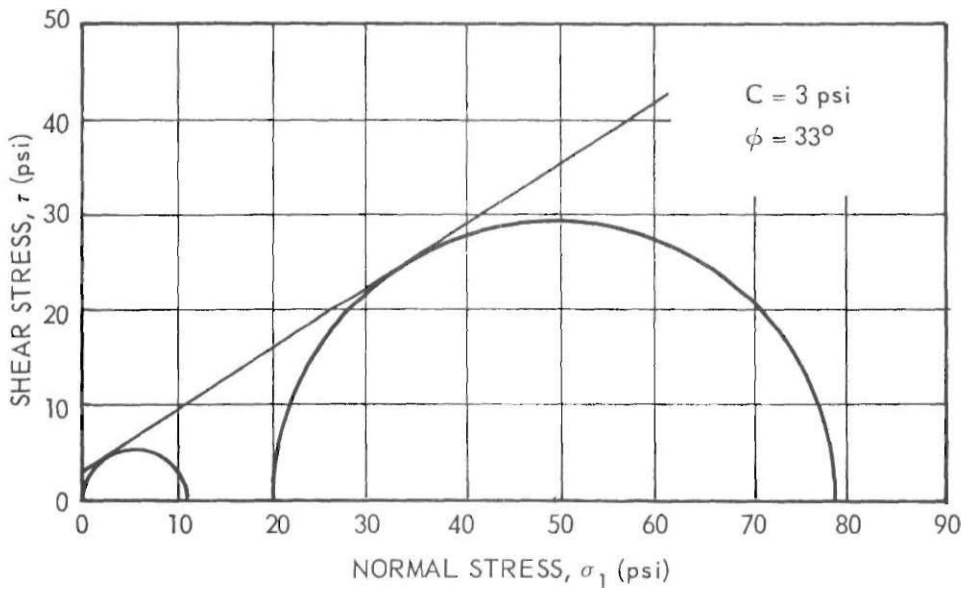

Figure 51. Mohr Diagram, Soil II + 4% RC-3, Stage 9.5.

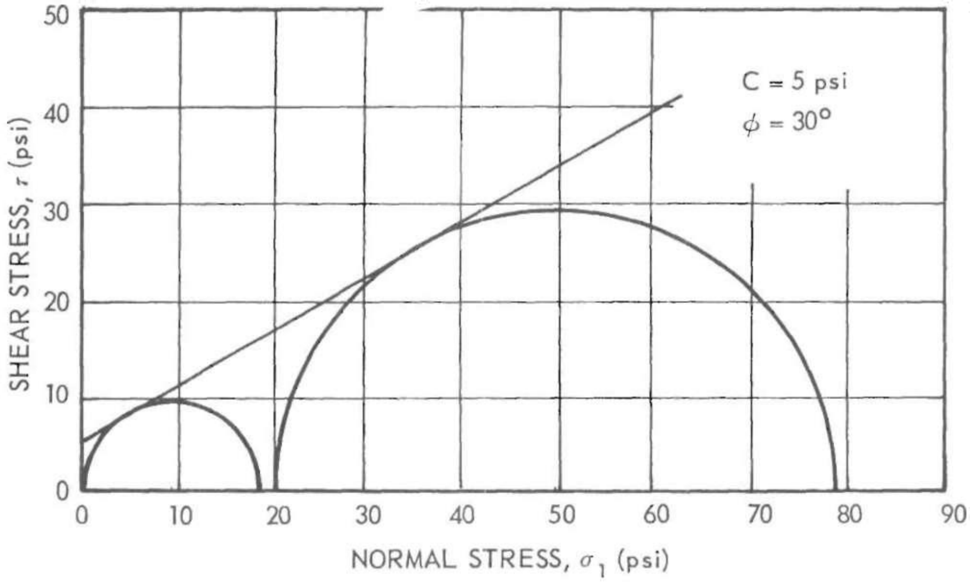

Figure 52. Mohr Diagram, Soil II + 4% RC-3, Stage 6.1.

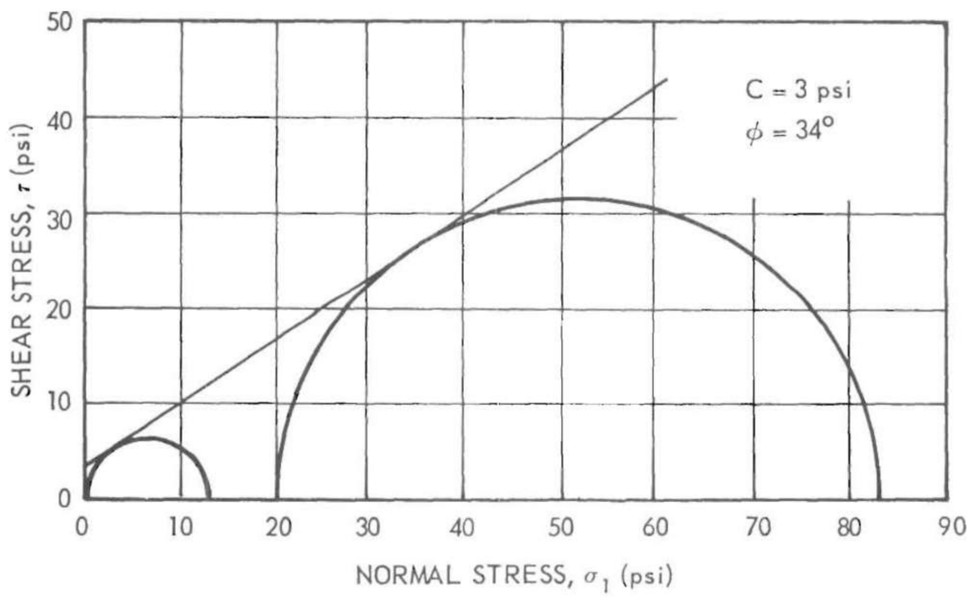

Figure 53. Mohr Diagram, Soil II + 6% RC-3, Stage Maximum.

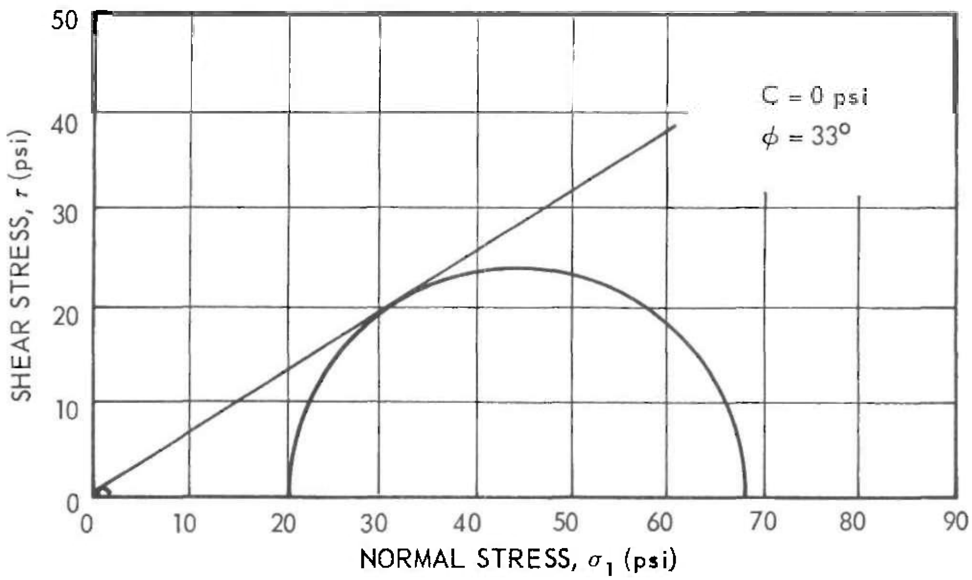

Figure 54. Mohr Diagram Soil III + 2% RC-3, Stage 5.3.

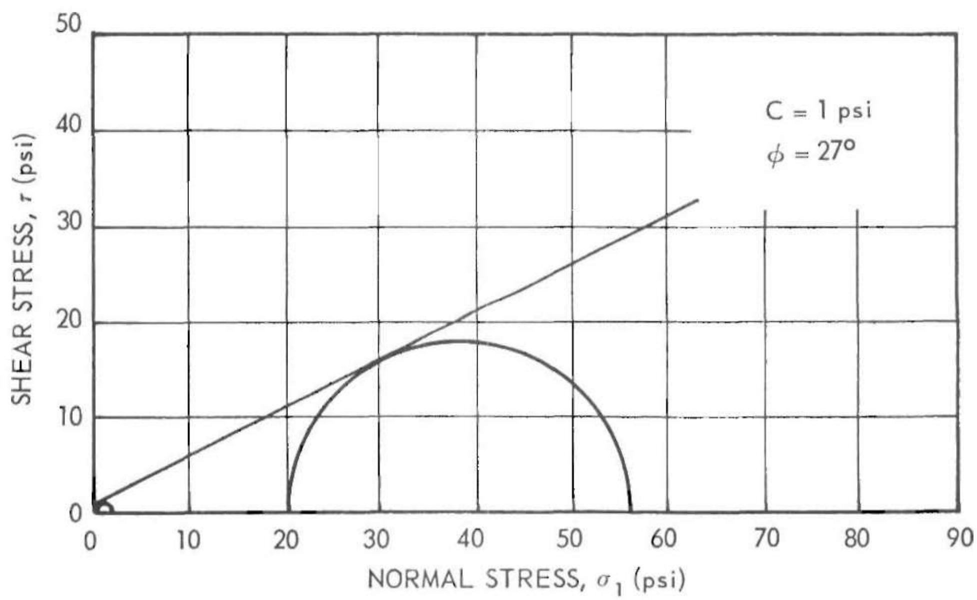

Figure 55. Mohr Diagram, Soil III + 2% RC-3, Stage 3.0.

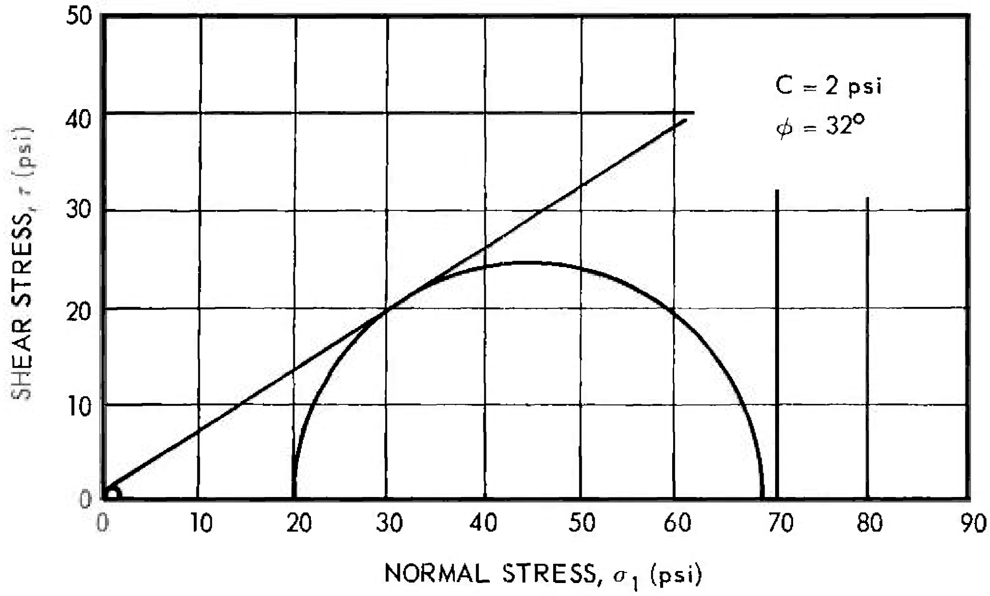

Figure 56. Mohr Diagram Soil III + 4% RC-3, Stage 5.3.

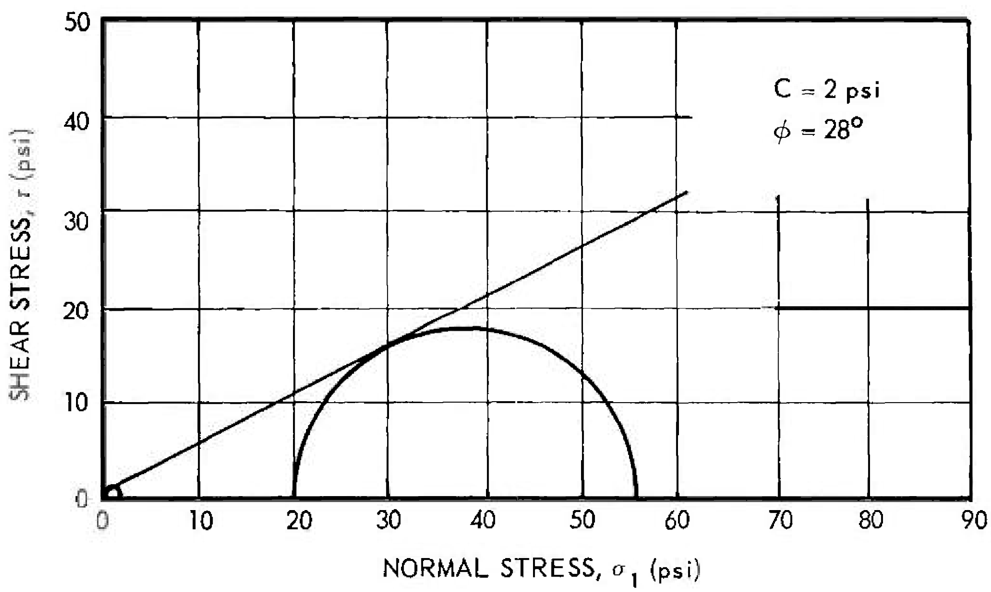

Figure 57. Mohr Diagram, Soil III + 4% RC-3, Stage 2.7.

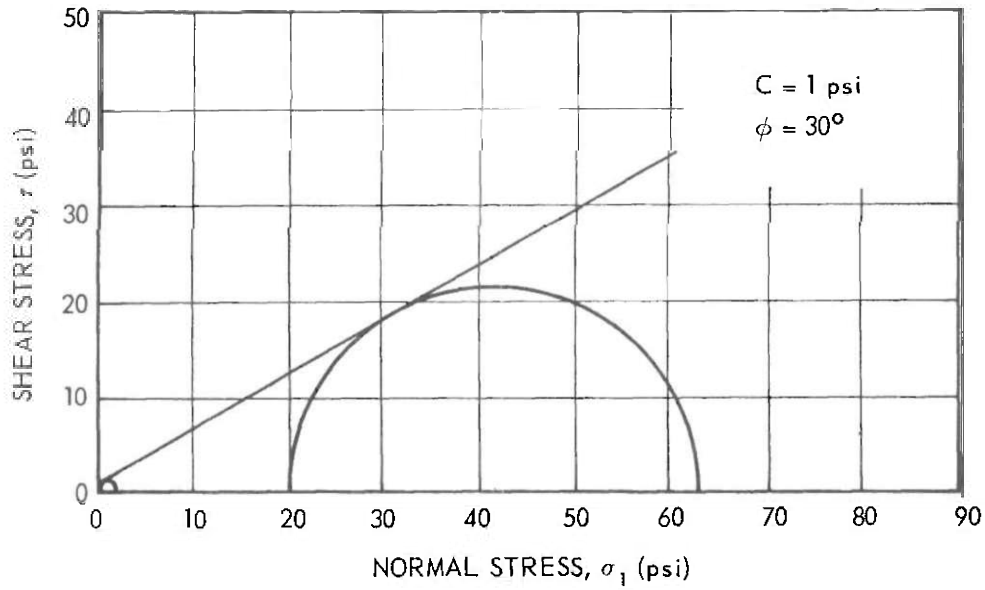

Figure 58. Mohr Diagram, Soil III + 6% RC-3, Stage 3.2.

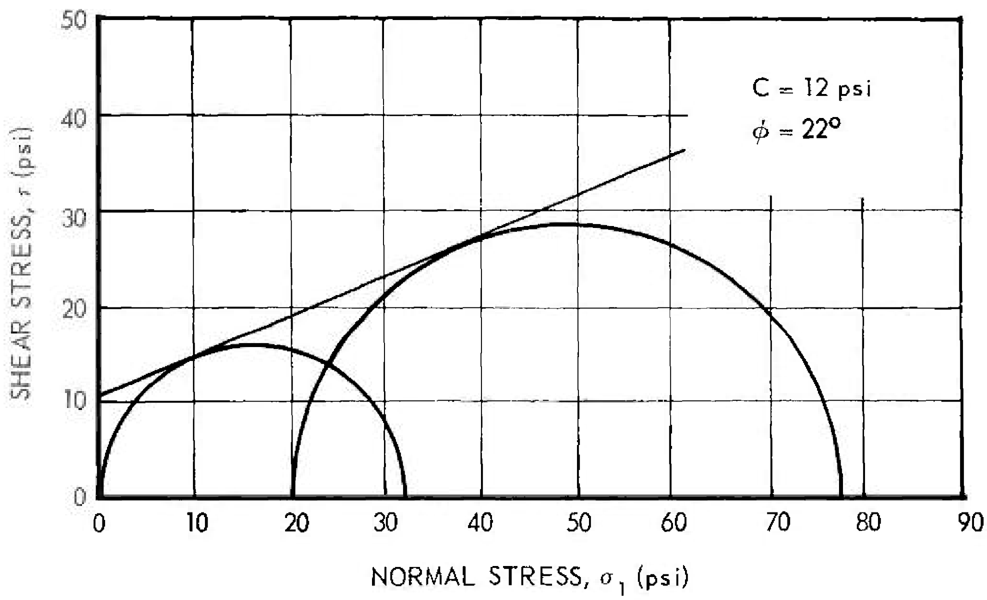

Figure 59. Mohr Diagram, Soil IV.

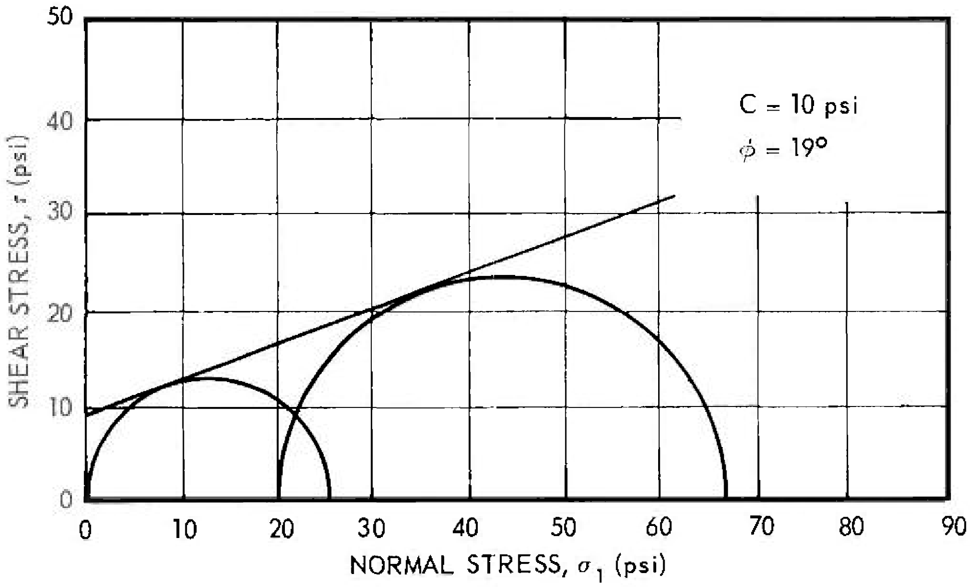

Figure 60. Mohr Diagram, Soil IV + 2% RC-3, Stage Maximum.

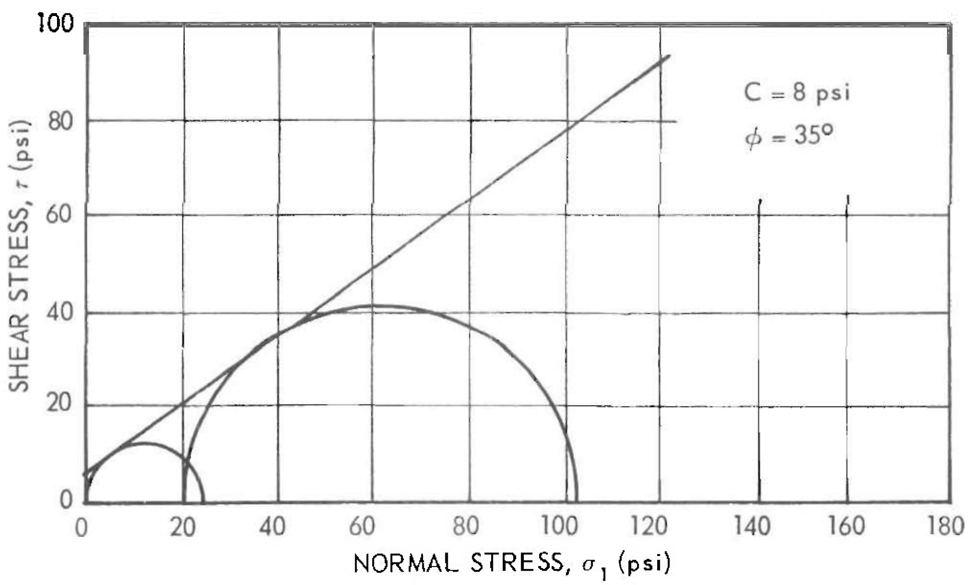

Figure 61. Mohr Diagram, Soil IV + 2% RC-3, Stage 10.9.

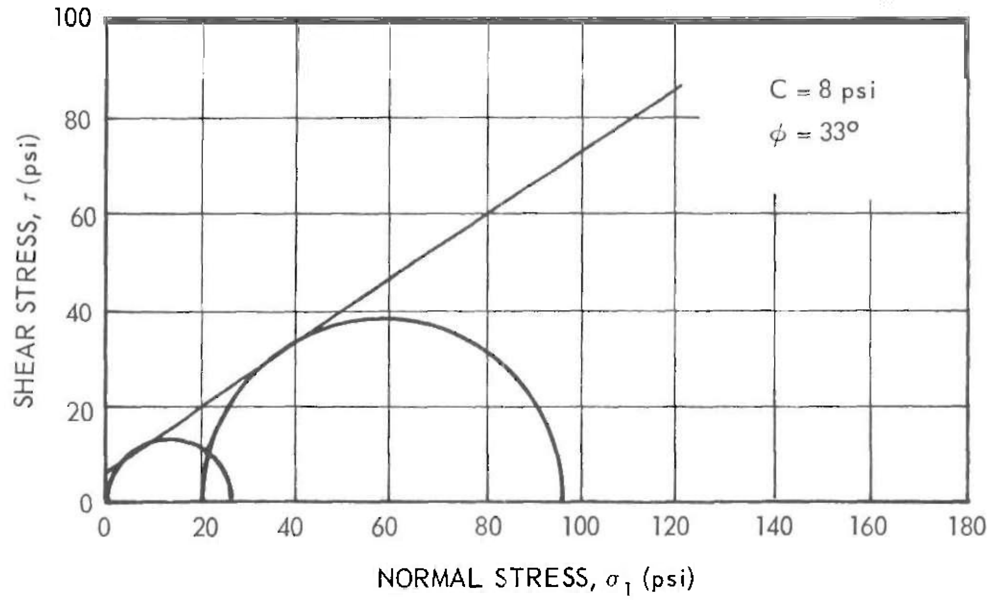

Figure 62. Mohr Diagram, Soil IV + 2% RC-3, Stage 11.7

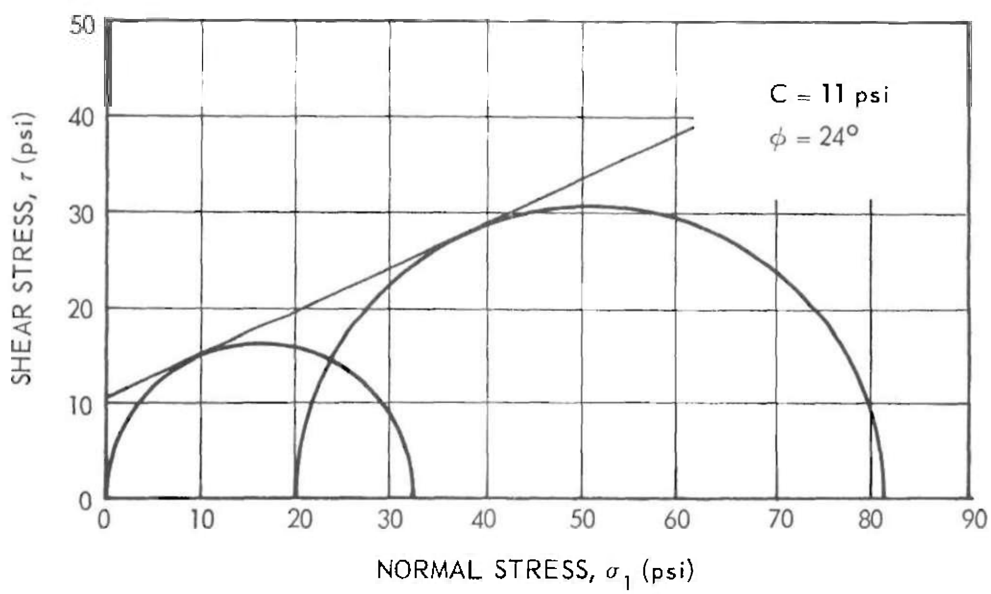

Figure 63. Mohr Diagram, Soil IV + 4% RC-3, Stage Maximum.

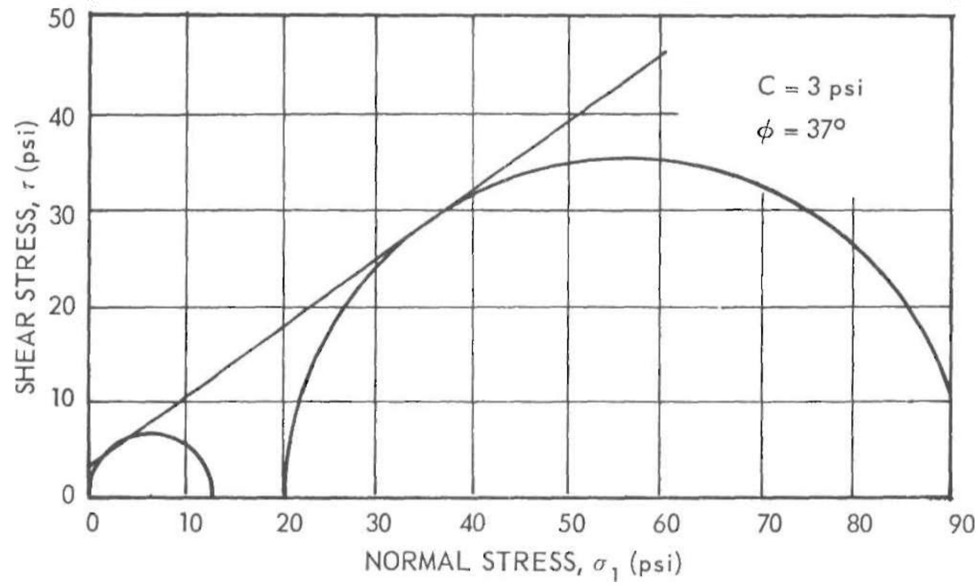

Figure 64. Mohr Diagram, Soil IV + 4% RC-3, Stage 9.3.

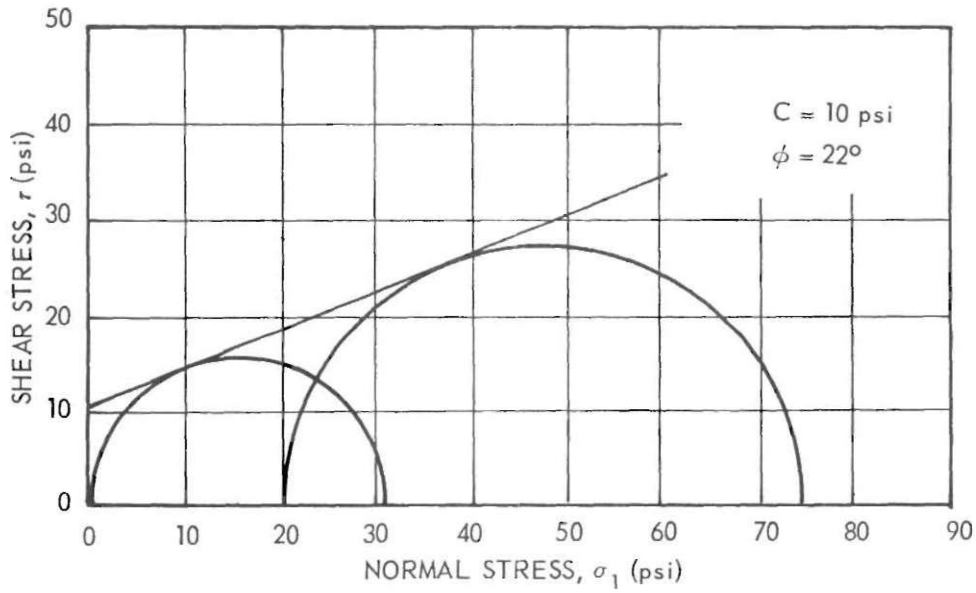

Figure 65. Mohr Diagram, Soil IV + 6% RC-3, Stage Maximum.

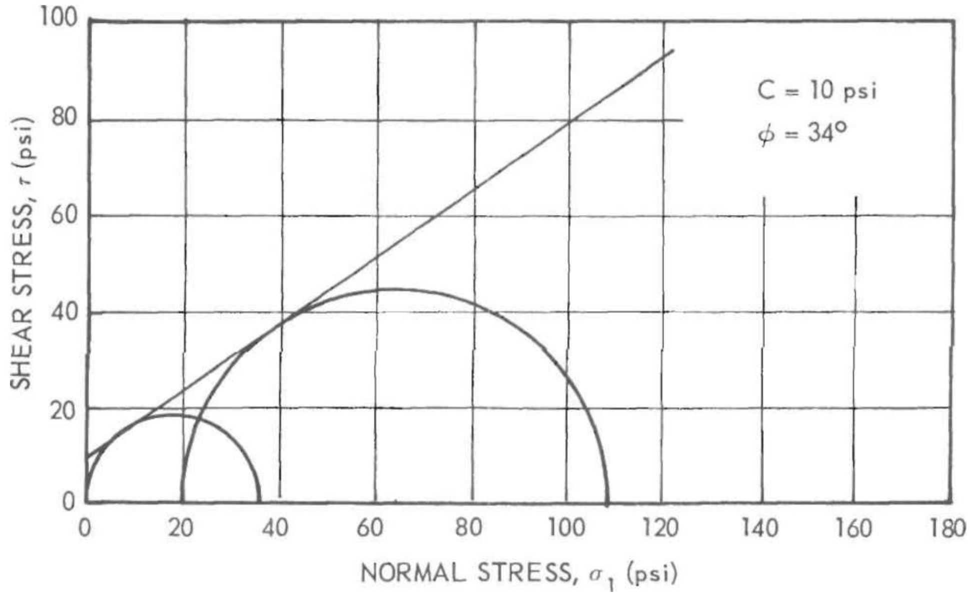

Figure 66. Mohr Diagram, Soil VI.

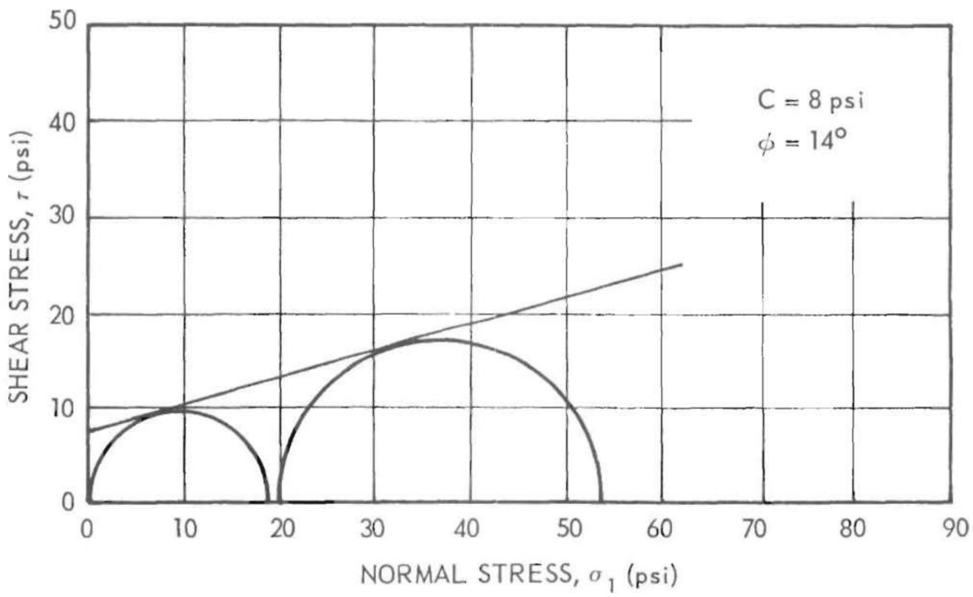

Figure 67. Mohr Diagram, Soil VI + 2% RC-3, Stage Maximum.

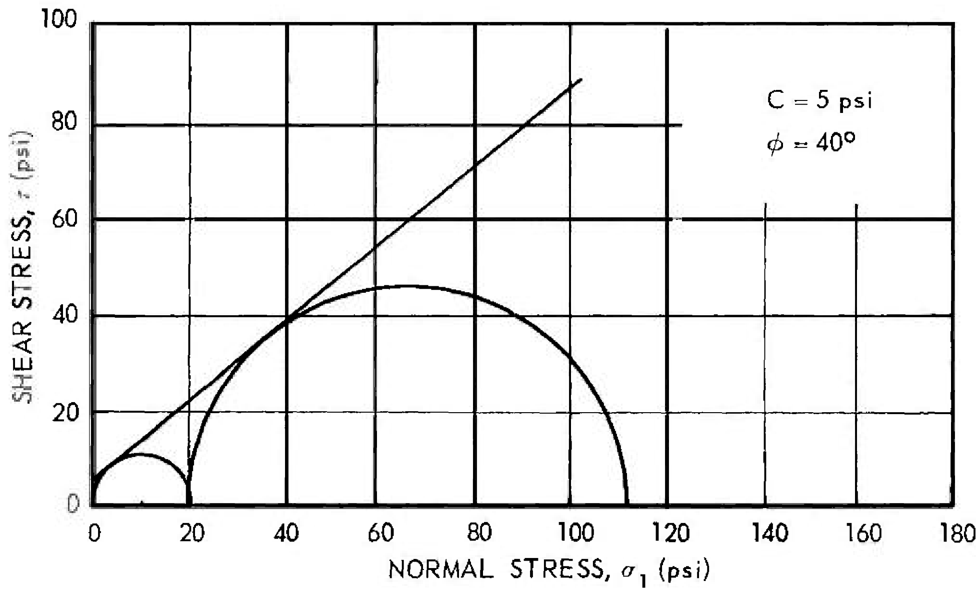

Figure 68. Mohr Diagram, Soil VI + 2% RC-3, Stage 11.2

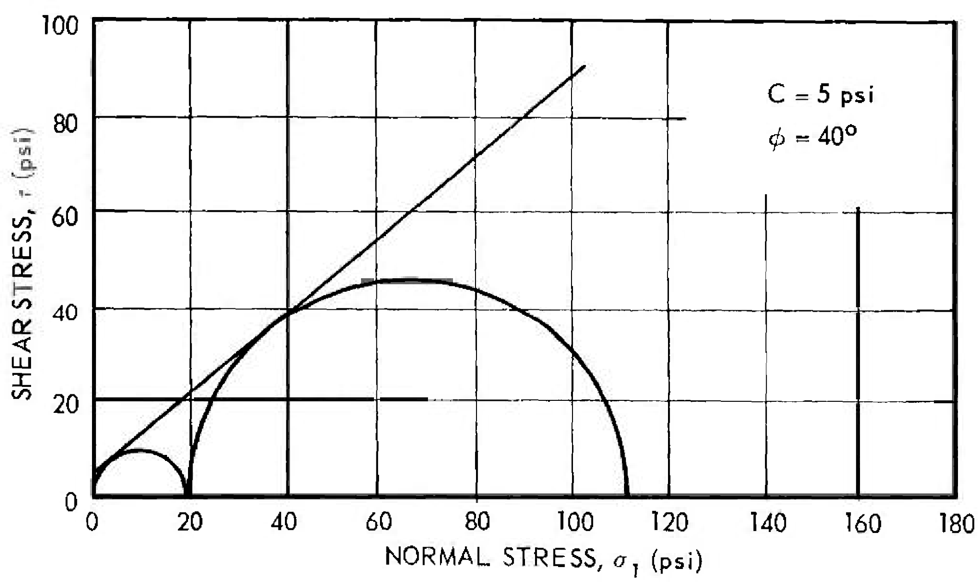

Figure 69. Mohr Diagram, Soil VI + 2% RC-3, Stage 10.3.

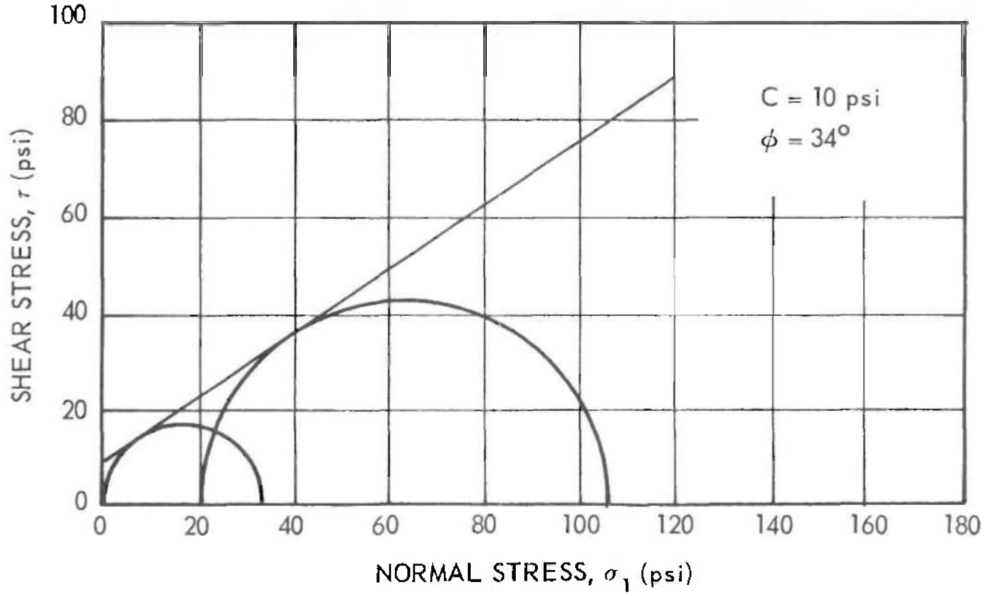

Figure 70. Mohr Diagram, Soil VI + 4% RC-3, Stage Maximum.

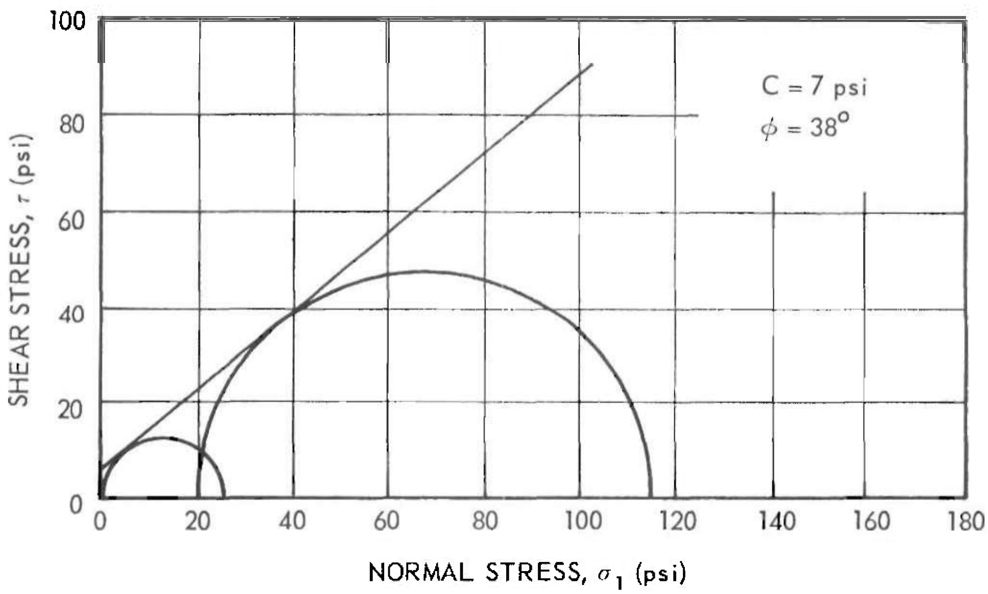

Figure 71. Mohr Diagram, Soil VI + 4% RC-3, Stage 9.7.

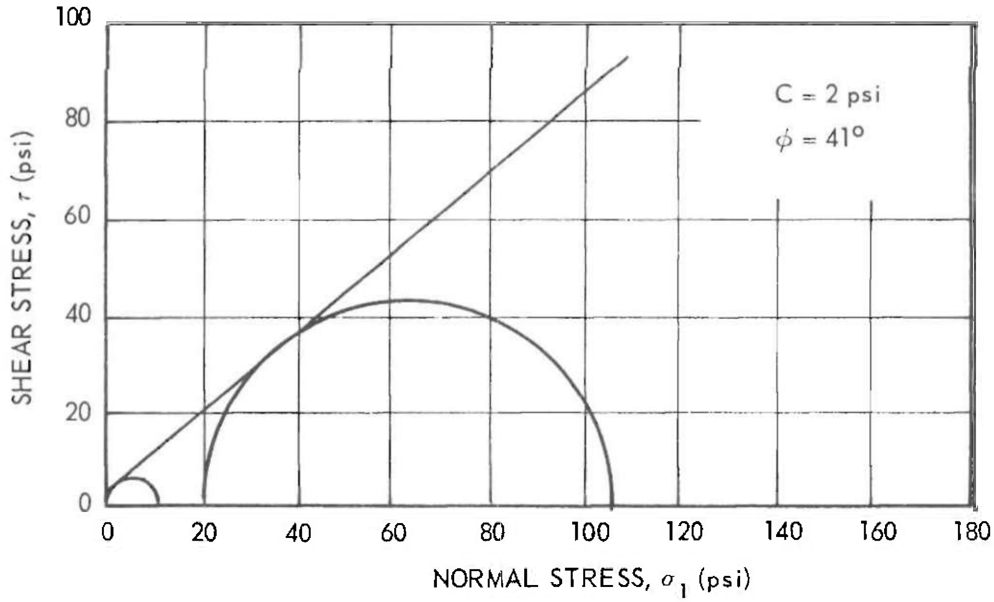

Figure 72. Mohr Diagram, Soil VI + 4% RC-3, Stage 7.8.

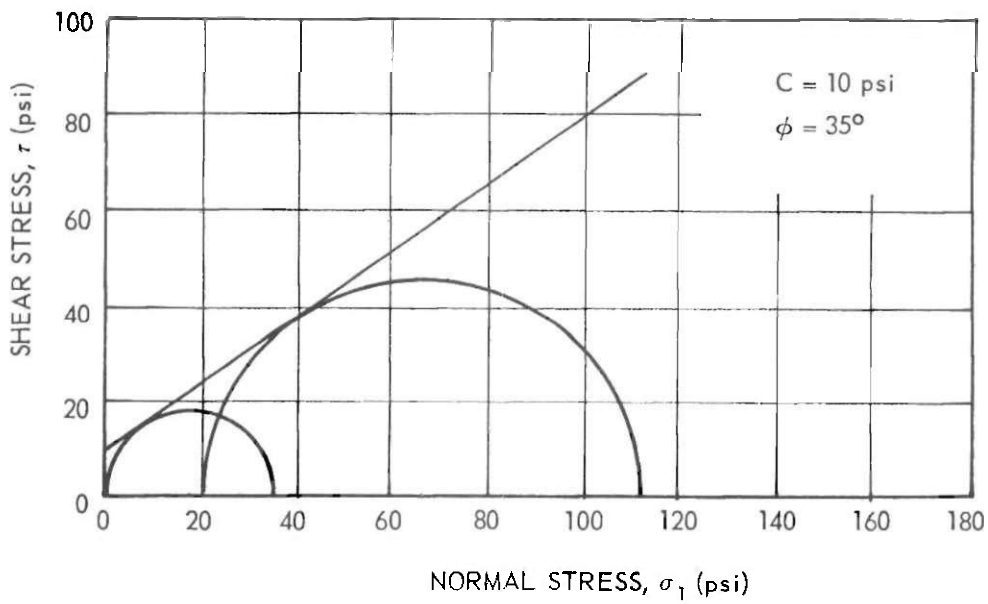

Figure 73. Mohr Diagram, Soil VI + 6% RC-3, Stage Maximum.

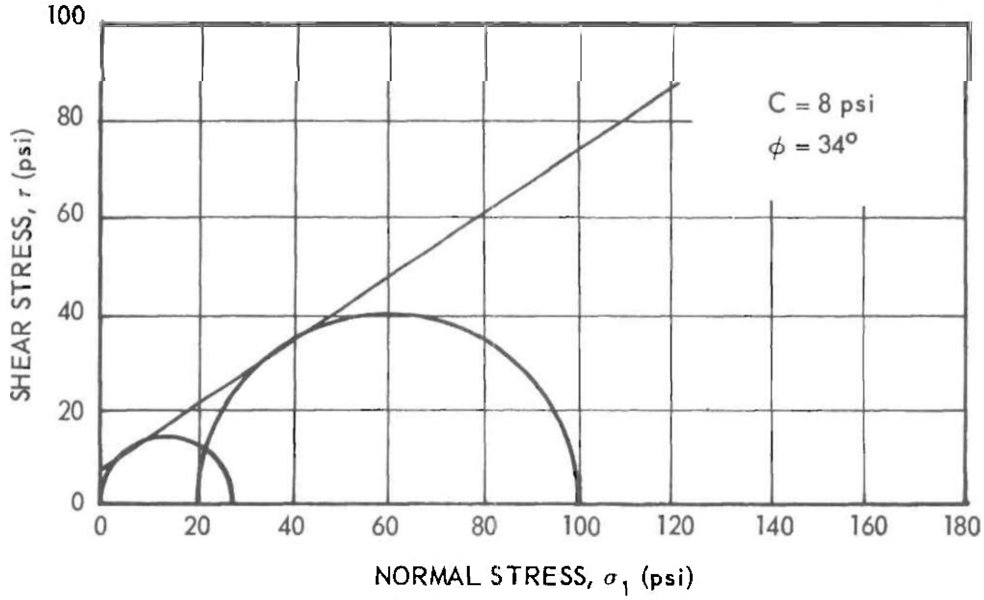

Figure 74. Mohr Diagram, Soil VI + 6% RC-3, Stage 11.2.

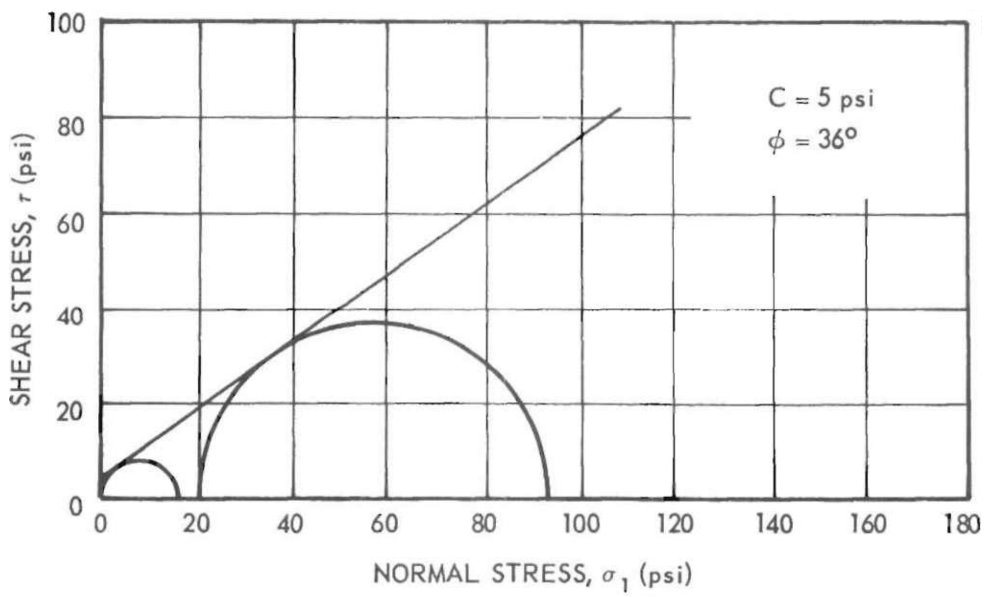

Figure 75. Mohr Diagram, Soil VI + 6% RC-3, Stage 10.0.

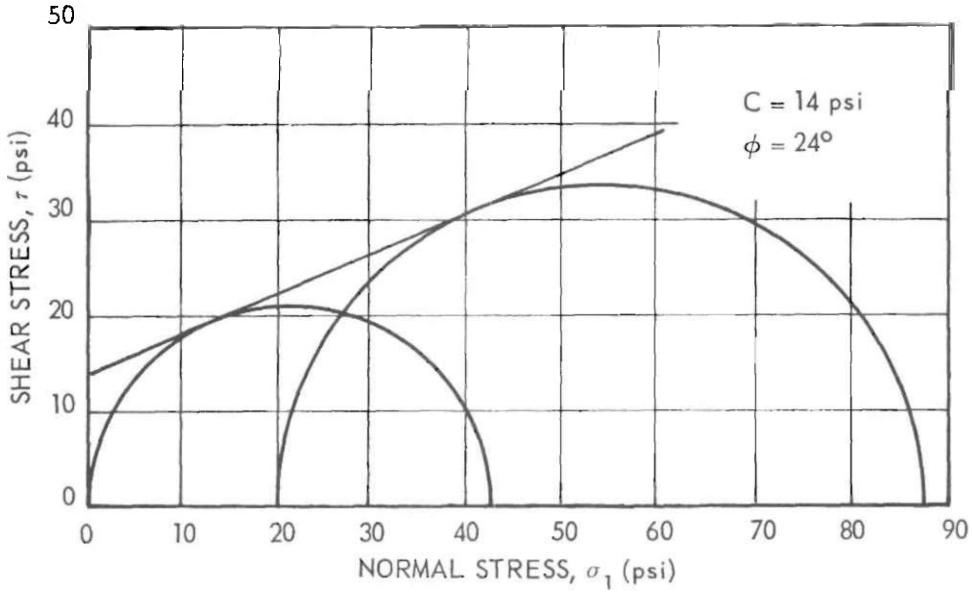

Figure 76. Mohr Diagram, Soil VII.

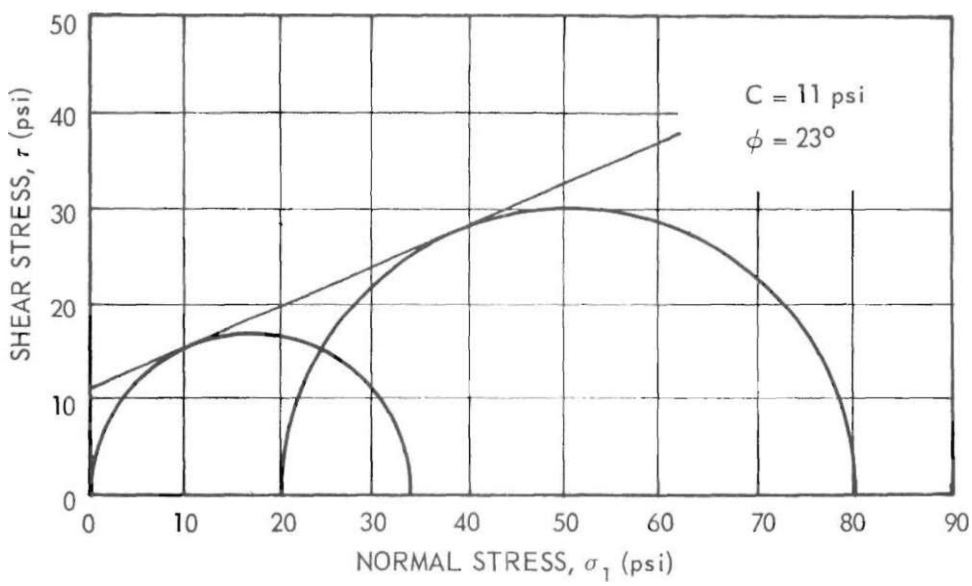

Figure 77. Mohr Diagram, Soil VII + 2% RC-3, Stage Maximum.

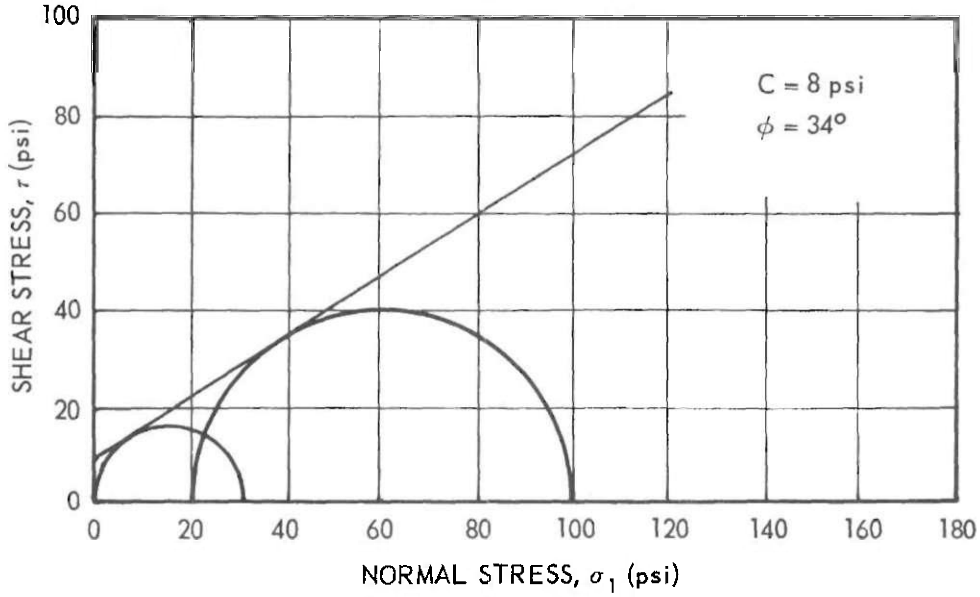

Figure 78. Mohr Diagram, Soil VII + 2% RC-3, Stage 10.6.

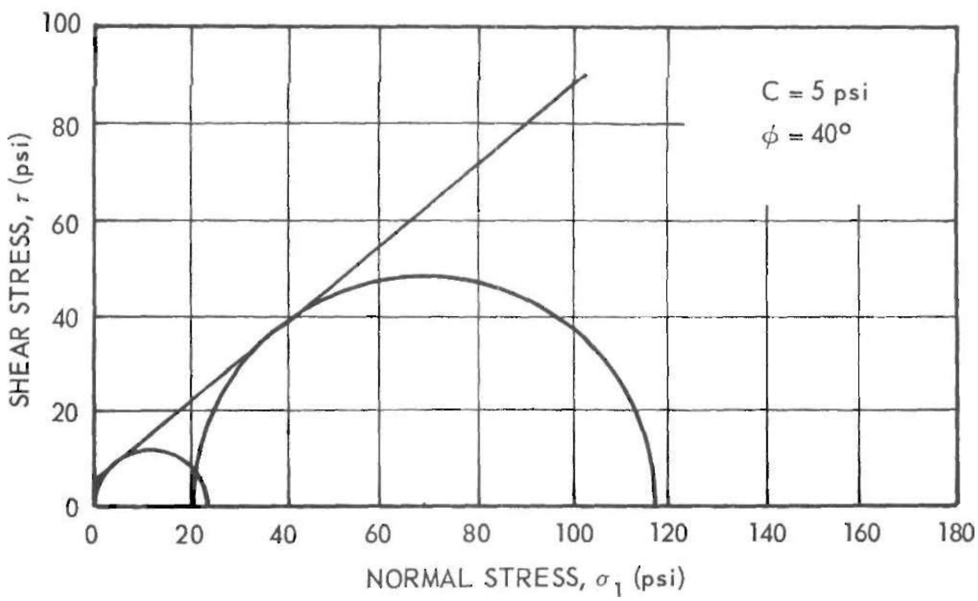

Figure 79. Mohr Diagram, Soil VII + 2% RC-3, Stage 8.4.

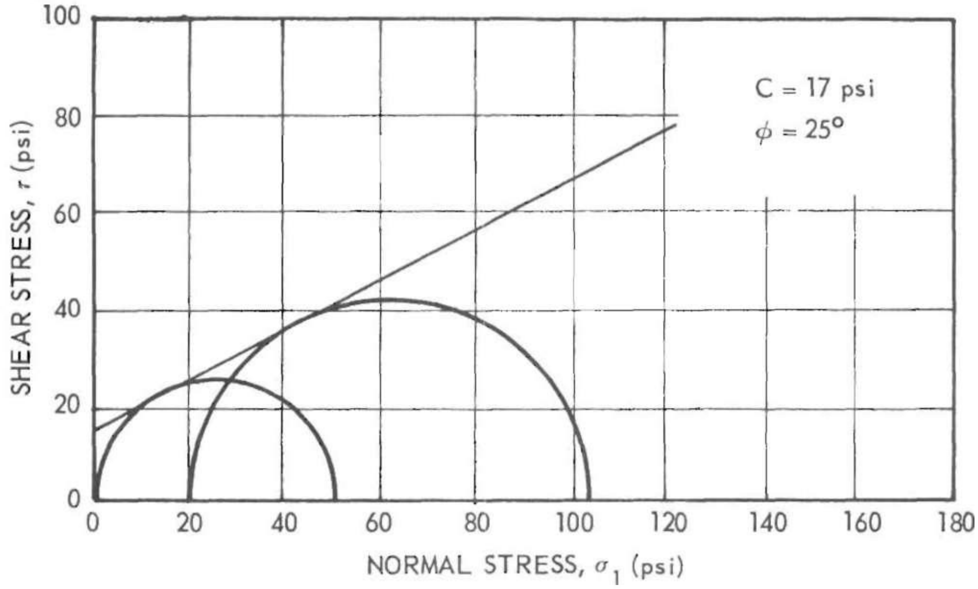

Figure 80. Mohr Diagram, Soil VII + 4% RC-3, Stage Maximum.

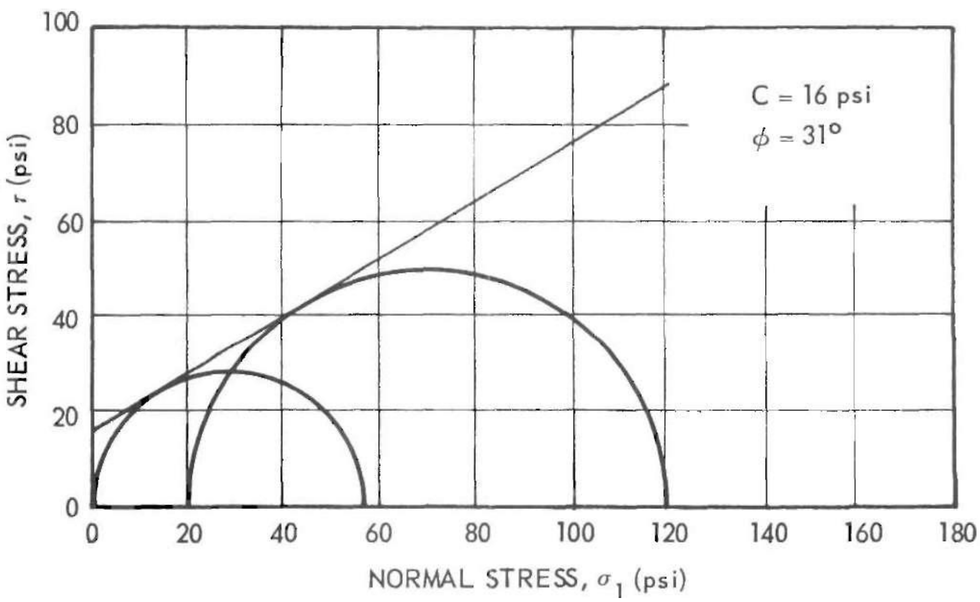

Figure 81. Mohr Diagram, Soil VII + 4% RC-3, Stage 9.7.

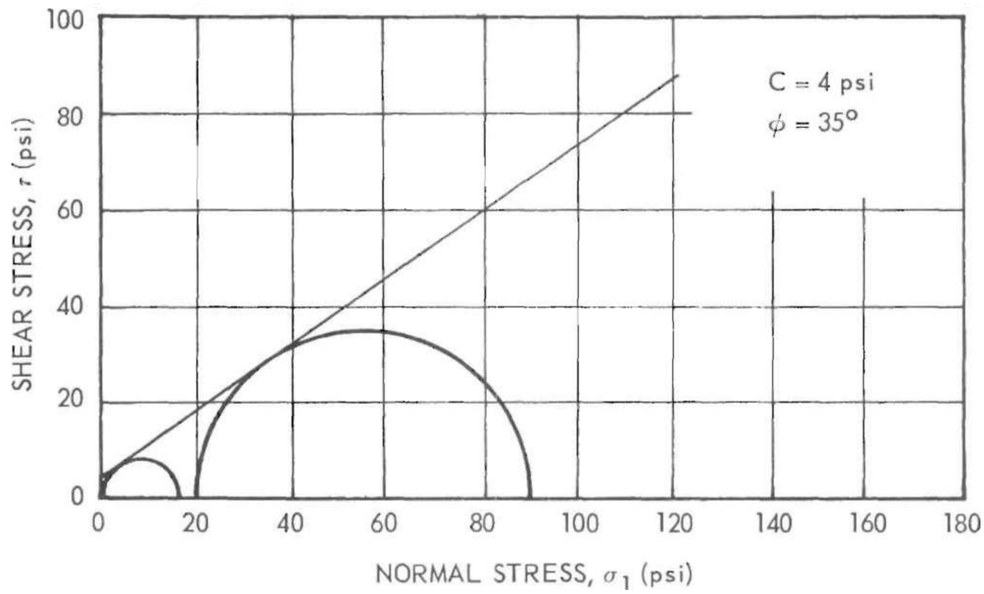

Figure 82. Mohr Diagram, Soil VII + 4% RC-3, Stage 8.0.

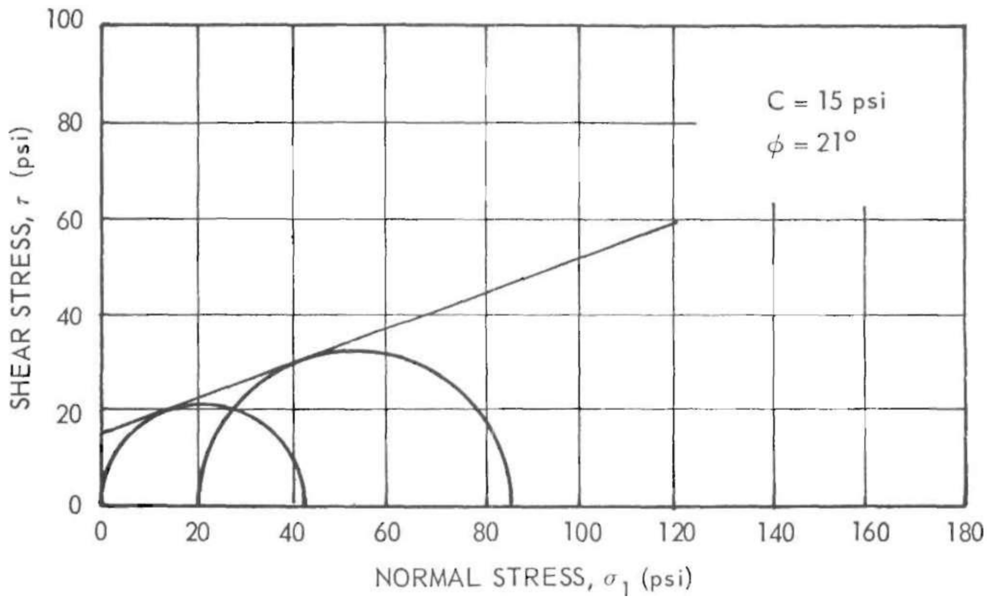

Figure 83. Mohr Diagram, Soil VII + 6% RC-3, Stage Maximum.

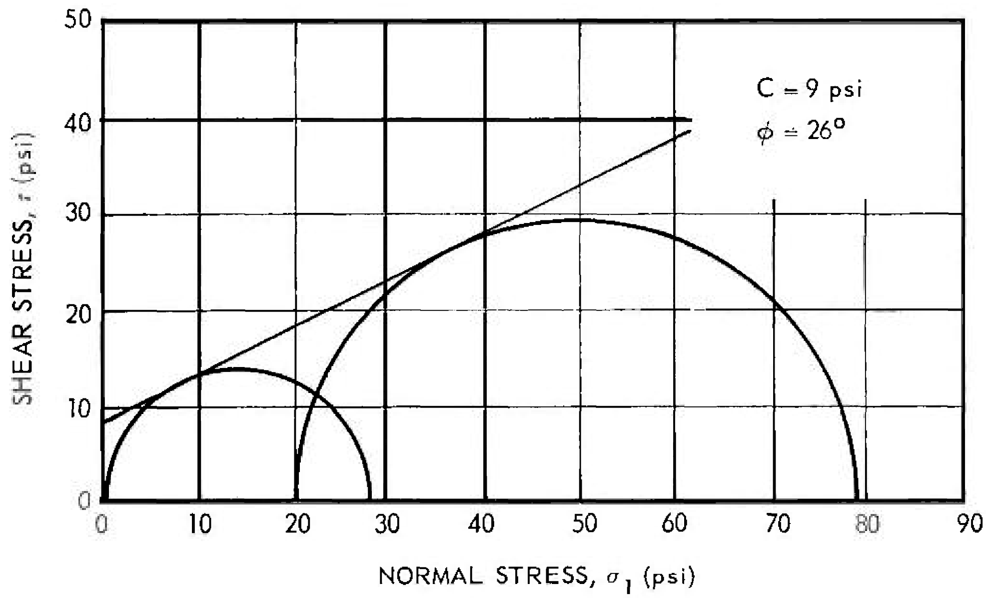

Figure 84. Mohr Diagram, Soil VII + 6% RC-3, Stage 9.3.

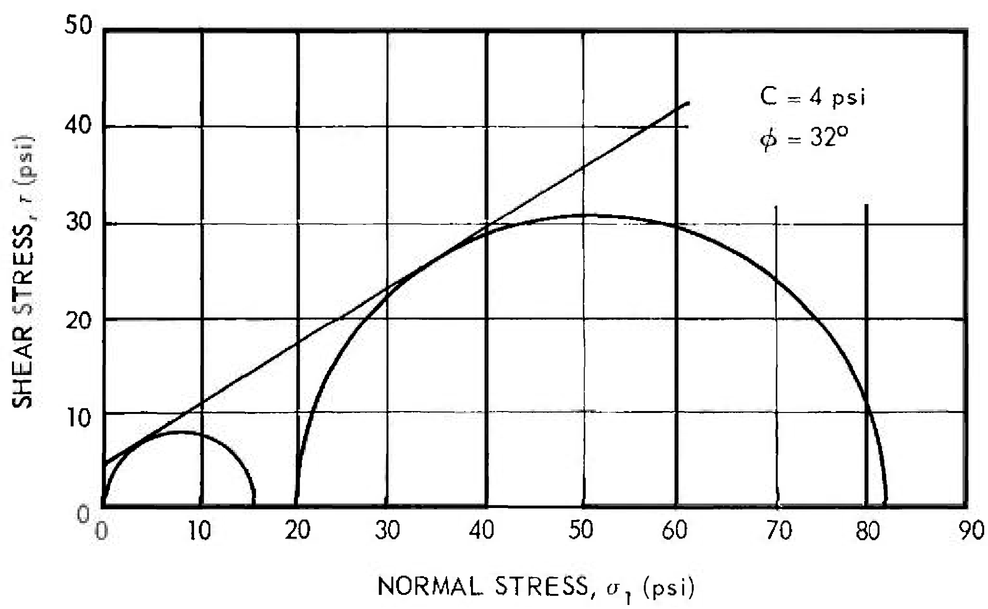

Figure 85. Mohr Diagram, Soil VII + 6% RC-3, Stage 8.0.

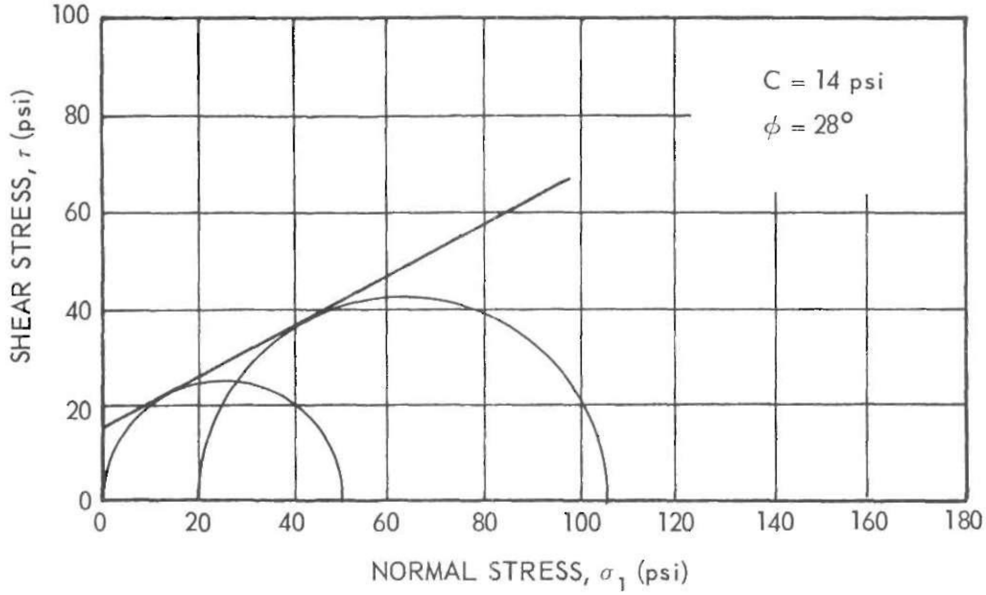

Figure 86. Mohr Diagram, Soil VIII + 2% RC-3, Stage Maximum.

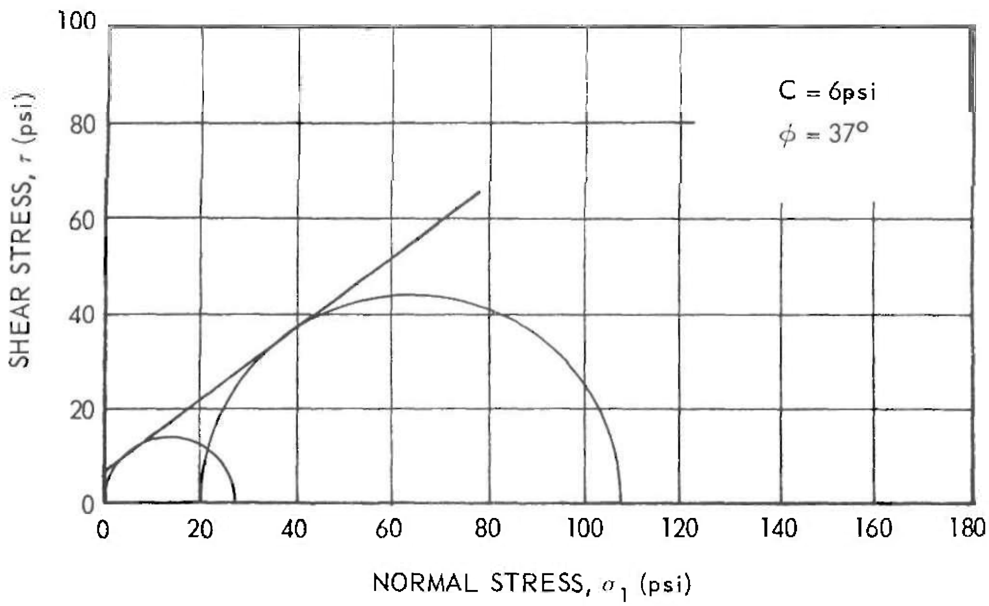

Figure 87. Mohr Diagram, Soil VIII + 2% RC-3, Stage 21.8.

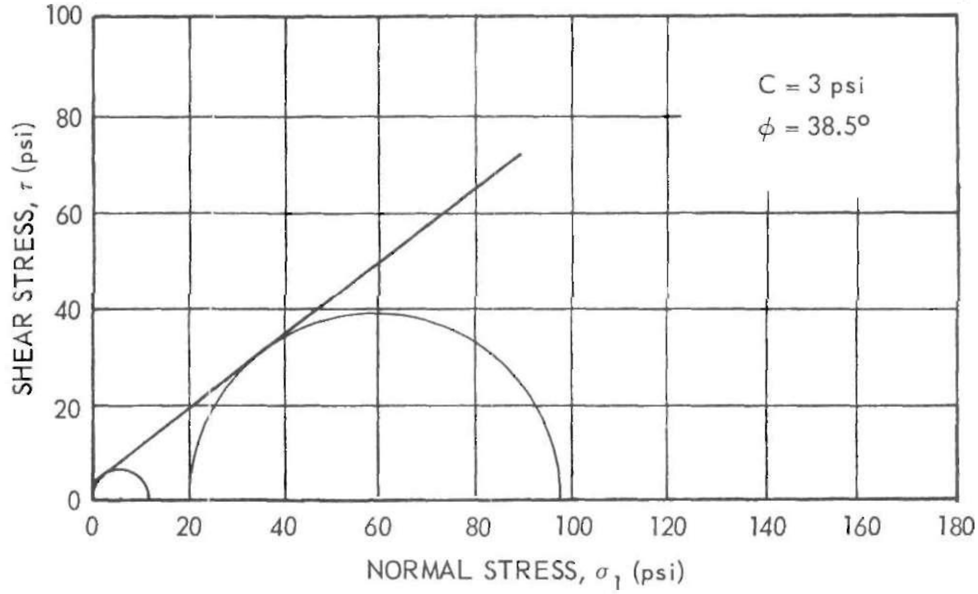

Figure 88. Mohr Diagram, Soil VIII + 2% RC-3, Stage 18.5.

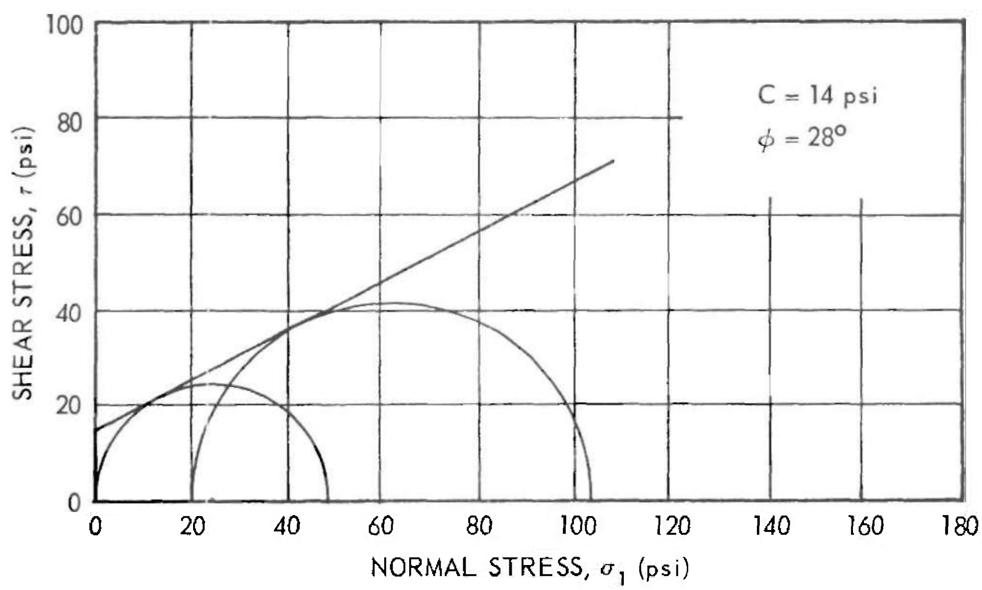

Figure 89. Mohr Diagram, Soil VIII + 4% RC-3, Stage Maximum.

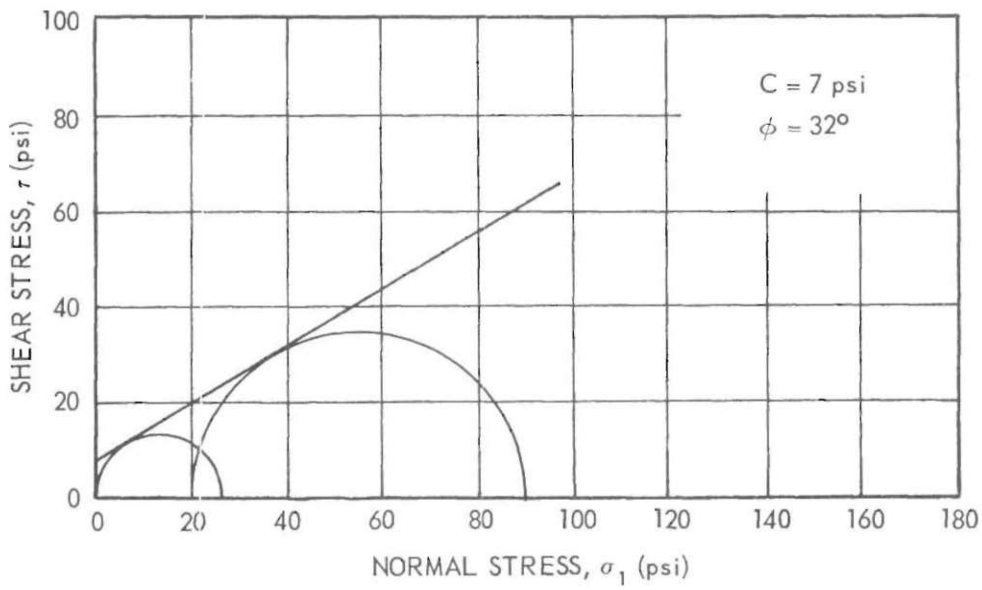

Figure 90. Mohr Diagram, Soil VIII + 4% RC-3, Stage 23.0.

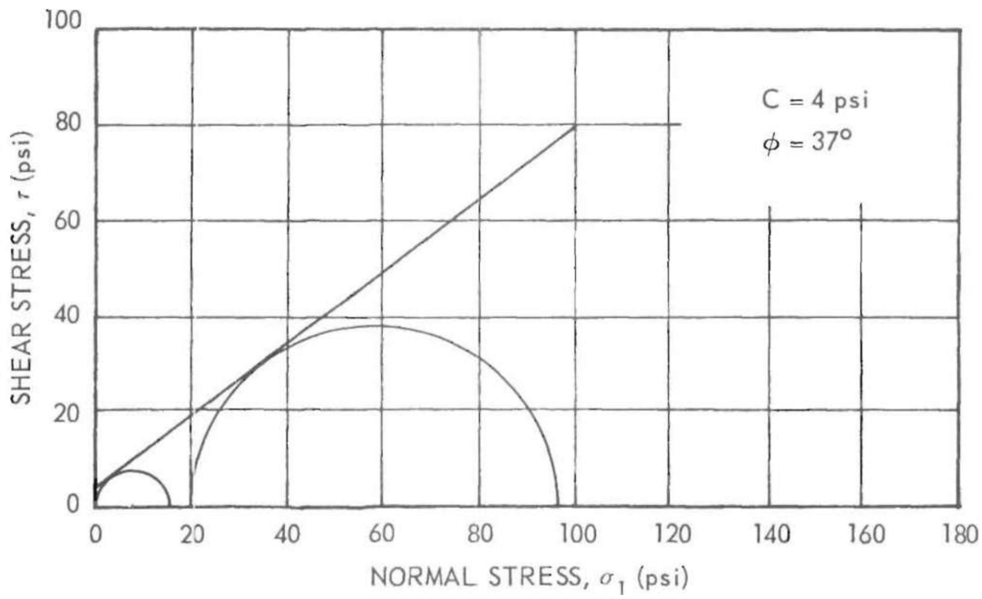

Figure 91. Mohr Diagram, Soil VIII + 4% RC-3, Stage 17.2.

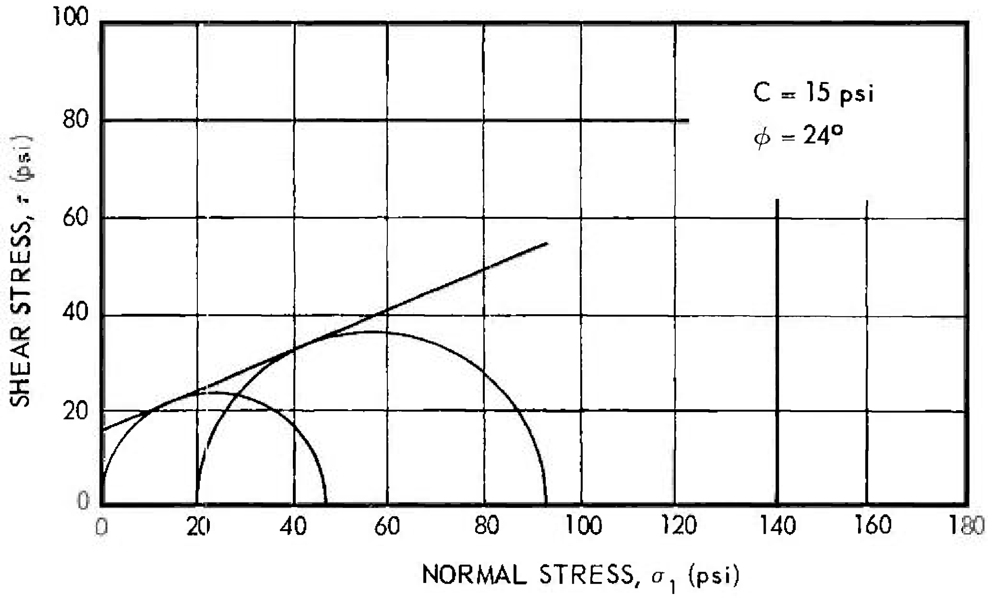

Figure 92. Mohr Diagram, Soil VIII + 6% RC-3, Stage Maximum.

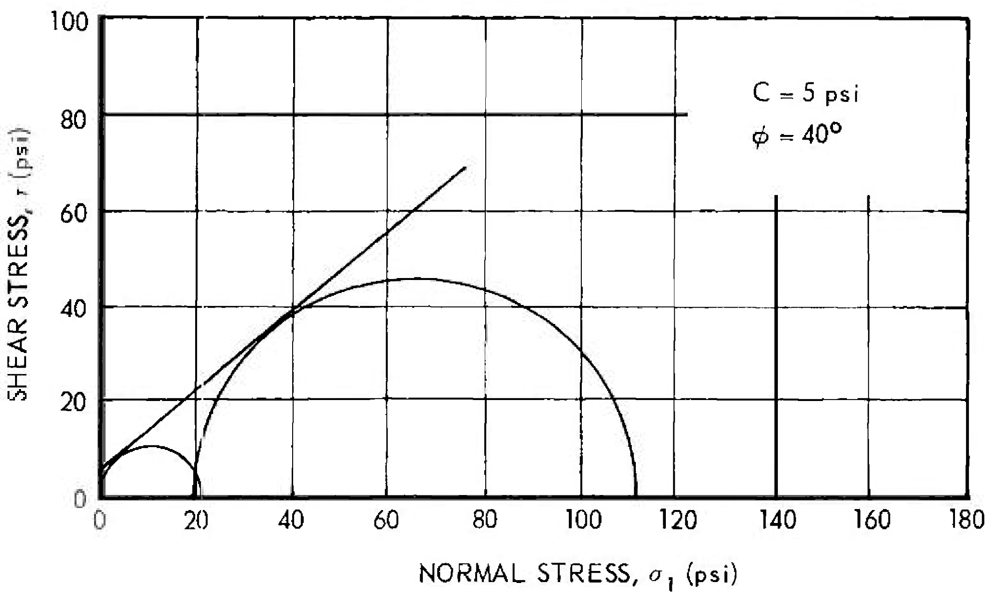

Figure 93. Mohr Diagram, Soil VIII + 6% RC-3, Stage 17.1.

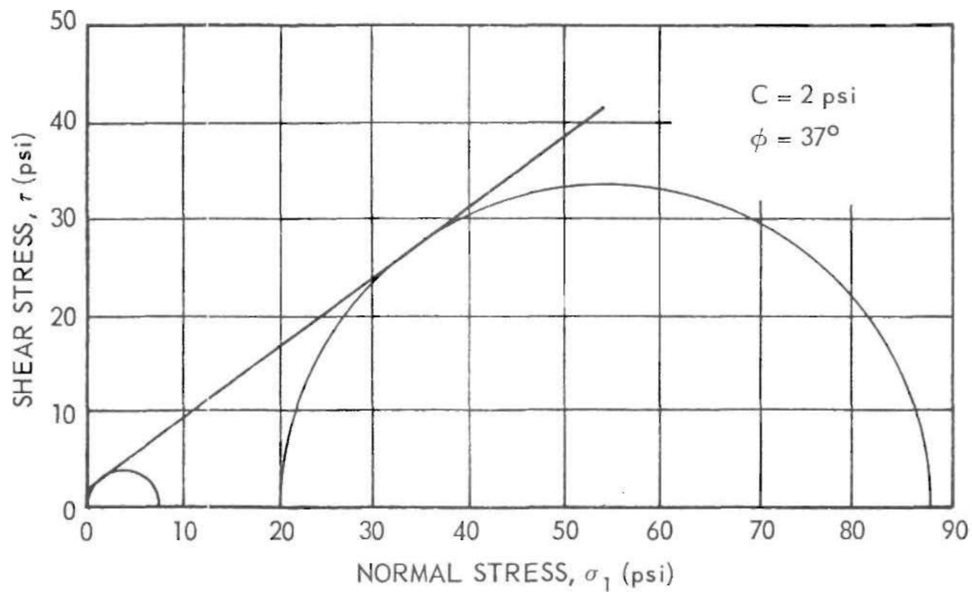

Figure 94. Mohr Diagram, Soil VIII + 6% RC-3, Stage 16.9.

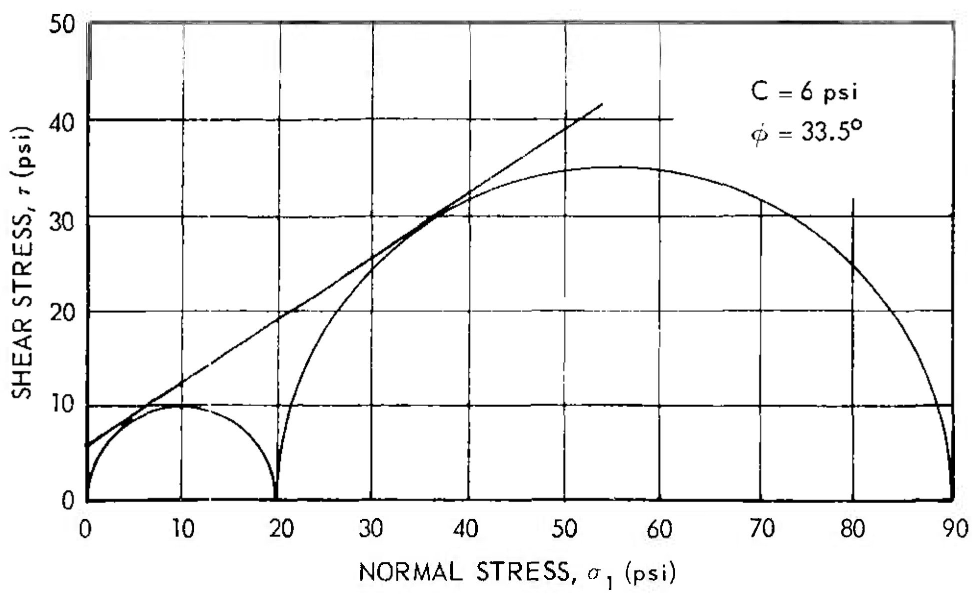

Figure 95. Mohr Diagram, Soil VIII + 6% RC-3, Stage 19.5.

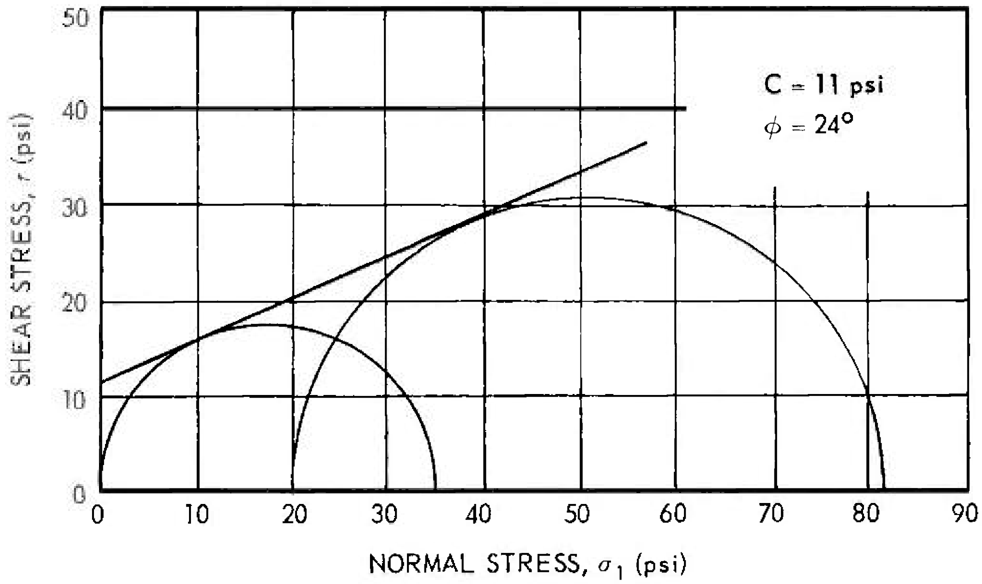

Figure 96. Mohr Diagram, Soil IX + 2% RC-3, Stage Maximum.

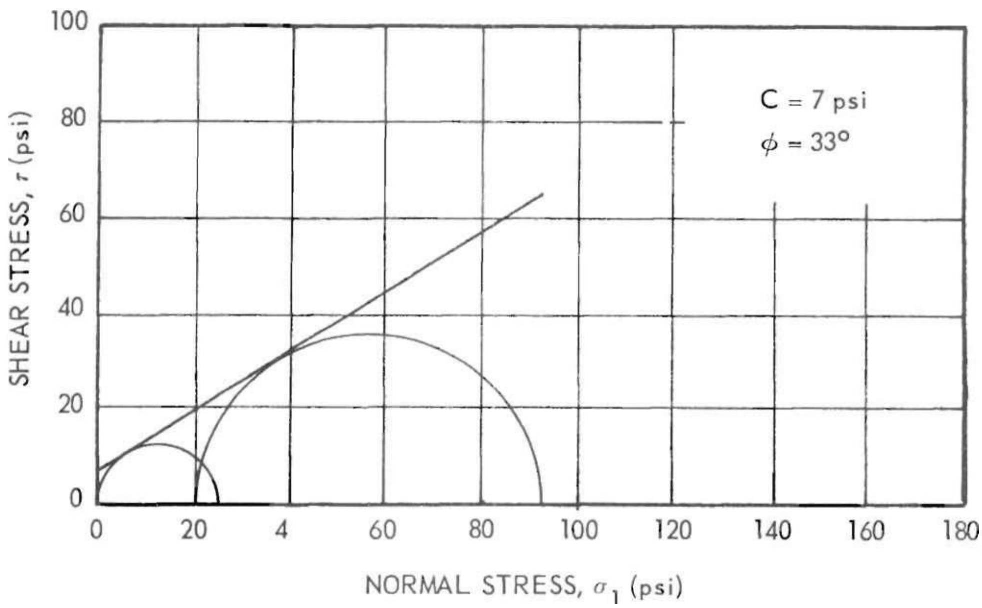

Figure 97. Mohr Diagram, Soil IX + 2% RC-3, Stage 21.3.

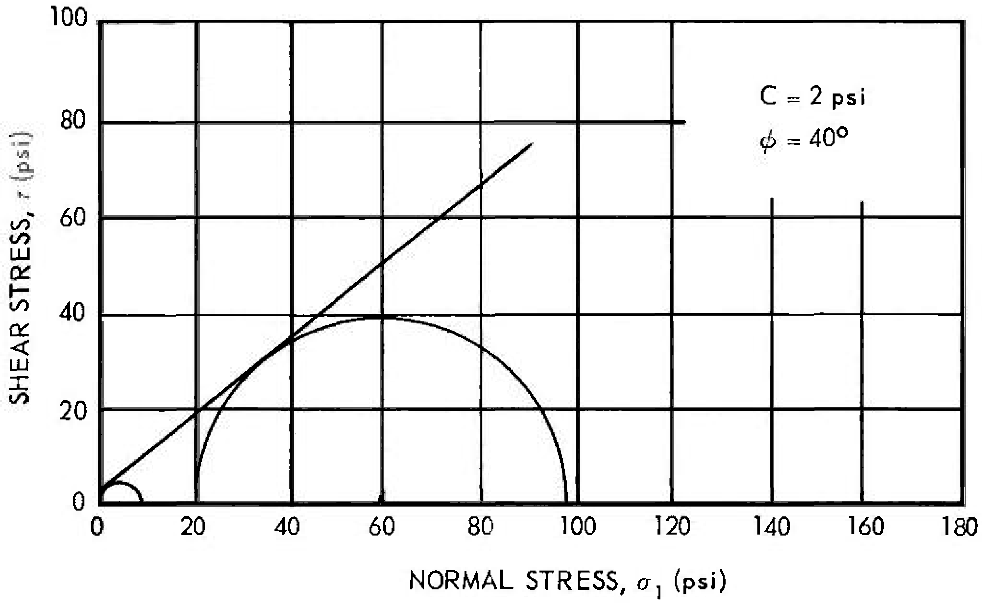

Figure 98. Mohr Diagram, Soil IX + 2% RC-3, Stage 15.8.

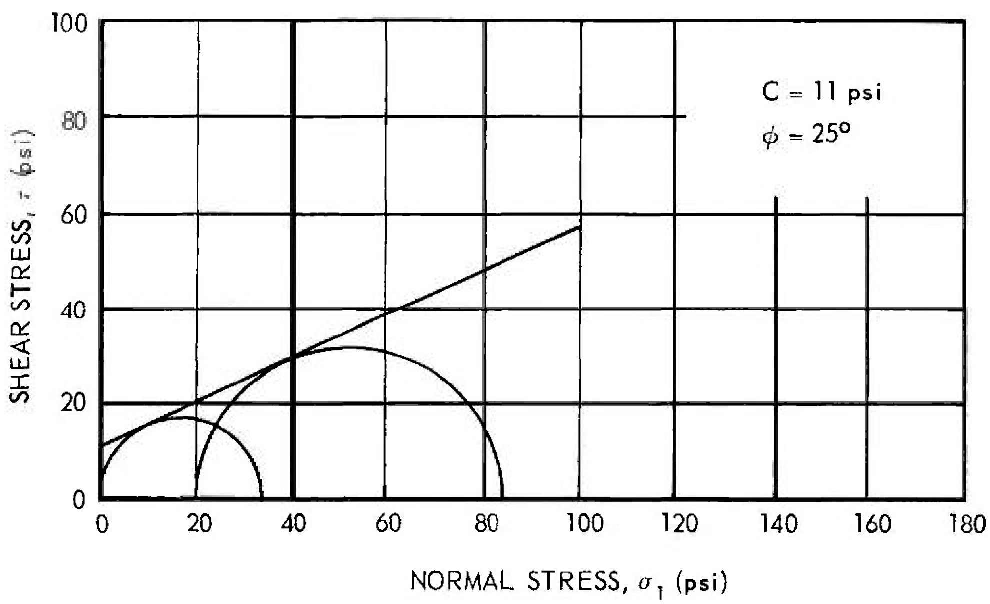

Figure 99. Mohr Diagram, Soil IX + 4% RC-3, Stage Maximum.

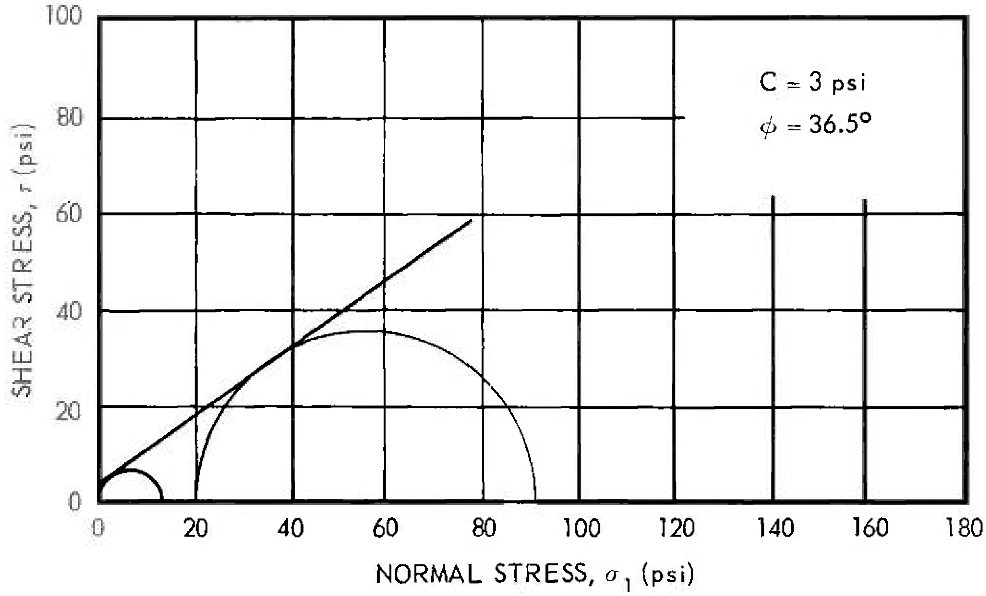

Figure 100. Mohr Diagram, Soil IX + 4% RC-3, Stage 16.7.

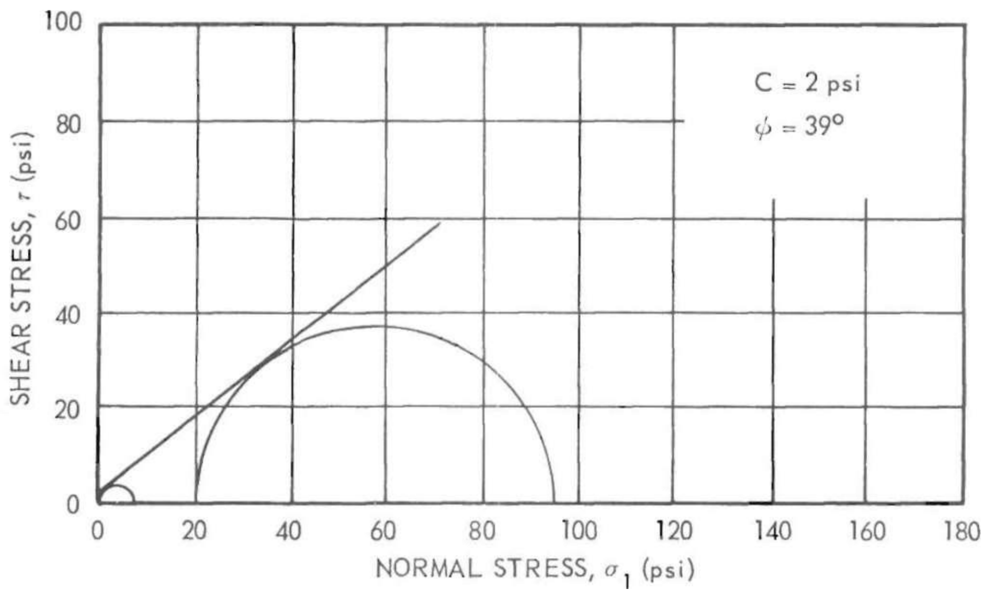

Figure 101. Mohr Diagram, Soil IX + 4% RC-3, Stage 14.2.

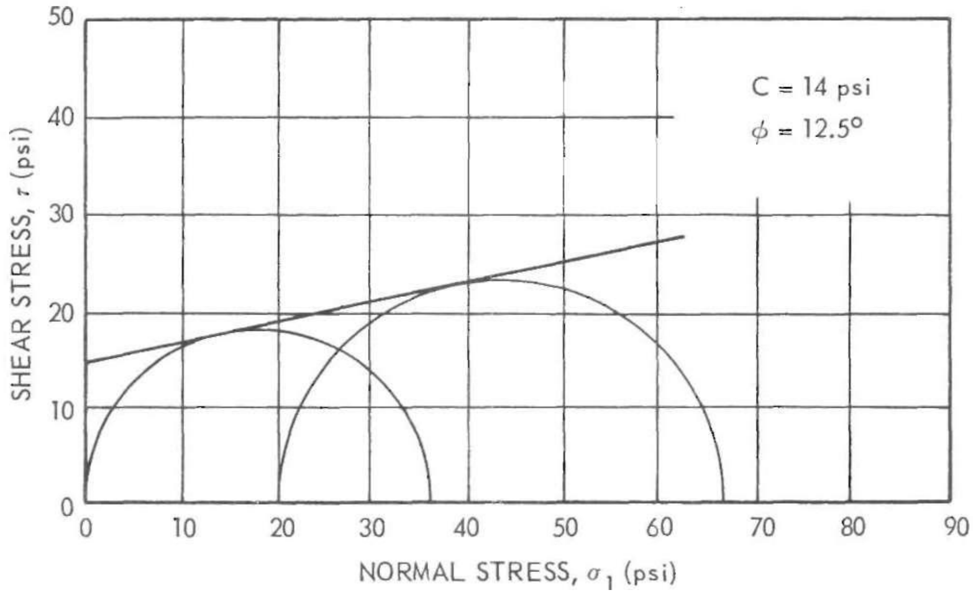

Figure 102. Mohr Diagram, Soil IX + 6% RC-3, Stage Maximum.

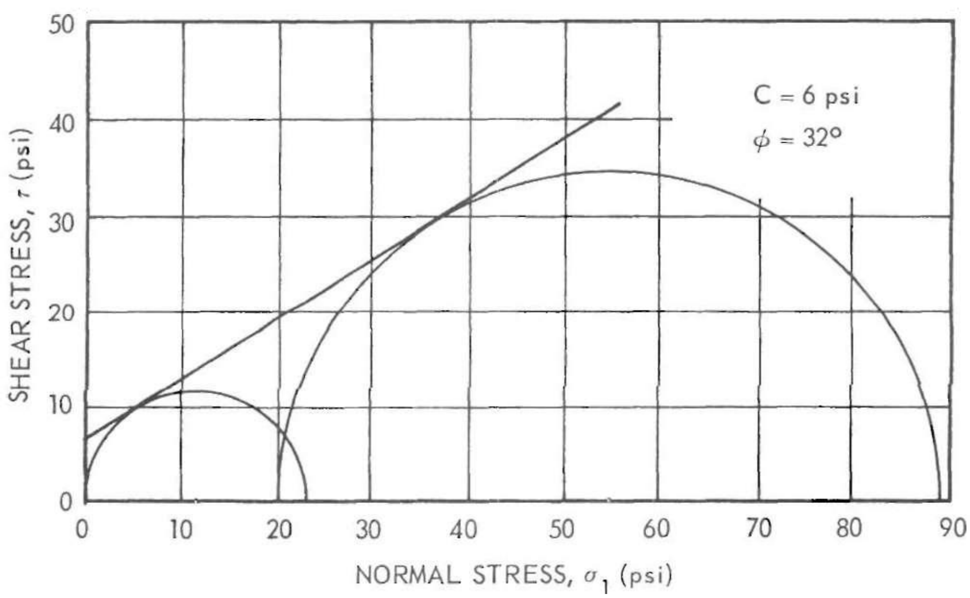

Figure 103. Mohr Diagram, Soil IX + 6% RC-3, Stage 17.9.

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